Good Practice

Guide 49

Energy efficient ladle pre-heating techniques within the steel industry

ENERGY EFFICIENCY

ENERGY EFFICIENT LADLE PRE-HEATING TECHNIQUES WITHIN THE STEEL INDUSTRY

This booklet is No. 49 in the Good Practice Guide Series, and it provides advice on practical ways of improving the energy efficiency of lade pre-heating techniques in the steel industry. It considers the various ladle heating systems currently used, and gives an action plan which can be applied to existing installations or used for selecting new installations to ensure improved energy use.

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FOREWORD

This Guide is part of a series produced by the Department of the Environment under the Energy Efficiency Best Practice programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded strips for easy reference:

- *Energy Consumption Guides:* (blue) energy consumption data to enable users to establish their relative energy efficiency performance;
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ENERGY EFFICIENT LADLE PRE-HEATING TECHNIQUES WITHIN THE STEEL INDUSTRY

1. INTRODUCTION

Ladles are used to transport molten steel inside the melting shop and prior heating of ladle refractories is an essential practice for safe and efficient operation. The heating requirements and practices vary from plant to plant, but in general the objectives are:

- to ensure that before the molten steel is poured into the ladles, the refractories and safety linings are completely dry;
- to reduce refractory damage caused by thermal shock on contact with molten steel;
- to reduce *skull** formation yield losses caused by steel chilling in the ladle;
- to minimise the reduction in molten steel temperature during tapping, transportation and the *teeming* processes.

Ladle heating is commonly achieved with gas or oil-fired burners at heating stations in the melting shop. In many instances, substantial energy savings are possible by using improved heating equipment, including waste heat recovery systems, and lower cost measures, such as good housekeeping practices. This Guide will show how energy savings can be achieved, including case histories illustrating the benefits and potential pitfalls.

The Guide is intended to:

- provide information on current and developing ladle heating practices;
- offer advice on the design and operation of energy efficient ladle heating systems;
- provide an action plan to improve efficiency.

The Guide is aimed at both technical and non-technical staff who intend to save energy in ladle heating operations.

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* Words and phrases in italics are explained in the glossary (Appendix 6).

2. ENERGY CONSIDERATIONS

2.1 Energy Use

Ladle heating consumes less energy than steel melting processes, and is often given a lower priority when considering improvements in energy efficiency. The majority of ladle heating stations do not use heat recovery techniques and, in some cases, little attention is paid to fuel economy.

In 1990 the UK produced nearly 18 Mt of crude steel, comprising approximately 13.5 Mt by the Basic Oxygen Steelmaking (BOS) route and 4.5 Mt by the Electric Arc Furnace (EAF) route. The mean specific fuel consumption of ladle heating stations has been estimated at 0.15 GJ/t for the BOS process and 0.3 GJ/t for the EAF process. This is equivalent to an annual energy consumption of 3.4 PJ (3.4×10^6 GJ)/annum (worth £8.5M based on a fuel price of £2.5/GJ) and an average specific energy consumption of 0.19 GJ/t crude steel.

The smaller ferrous foundries also use substantial amounts of energy for ladle heating and a recent survey[1] indicated that there are over 2000 ladle stations within the UK. Specific energy use is likely to be higher because of the smaller size and one typical station was estimated to consume 1 GJ/t. Although difficult to quantify, the total energy use could be in excess of 1.36 PJ (1.36×10^6 GJ)/annum (based on a combined steel and iron foundry production of 1.36 Mt in 1989).

2.2 Energy Efficiency

The specific energy consumption of ladle heating based on steel production (GJ/t) is an unrepresentative way of comparing ladle performance, because operating conditions vary between plants; for example, refractory practices, operating temperatures, scheduling, etc.

Performance is more effectively monitored by assessing ladle heating efficiency, which is the fraction of the energy input released to the ladle. However, this can be difficult to measure, and will vary over the heating cycle as the ladle temperature increases. A full energy balance is therefore required to evaluate the overall efficiency over a heating cycle, and the initial condition of the ladle must be taken into account. The baseline for comparing heating efficiencies should be newly bricked ladles heated from cold. Measurement techniques to obtain an overall energy balance are described in Appendix 1.

Spot checks of factors which indicate efficiency are generally easier to obtain but the results must be interpreted carefully, and the condition of the ladle must be considered when measurements are taken.

Heating efficiencies vary considerably depending upon the installation and the refractory structure; ie refractory thickness, thermal conductivity and specific heat requirement. Typical values can range from 5% for the most basic system to 65% for state-of-the-art combustion equipment with heat recovery techniques. Electrical heating systems are capable of higher efficiencies at point of use (up to 90% efficiency), but these are impractical for large ladle heating systems for the reasons given in Section 3.5. Fuel fired systems are more common but, because the best available technology is not generally used, in practice they only operate with heating efficiencies between 30 and 40%. Therefore, there is scope for substantial energy savings to be made on many such installations.

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[1] Department of Energy, EEDS, Expanded Project Profile 270, 'Improved Design for Foundry Ladle Pre-heaters'.

Energy savings can be made by a combination of improved heating equipment and lower cost measures. Equipment improvements include more effective hoods, correctly sized burners, heating controls and waste heat recovery systems. Lower cost measures include equipment maintenance, such as hood rim cleaning, and good melting shop management and housekeeping practices. Descriptions and examples of these measures are given in this Guide, and the Action Plan in Section 4 provides a summary.

In order to assess the costs of ladle heating, and evaluate the potential for savings, it is essential that fuel metering is installed. This is strongly recommended for all ladle heating installations.

2.3 Ladle Refractories

The characteristics of ladle refractories partly dictate the required heating cycle, and so affect energy consumption. This section briefly outlines refractory types, and identifies heating considerations.

Modern melting practices, which include ladle steelmaking and continuous casting, require ladles to hold steel for longer periods than with the traditional furnace/ingot route. Therefore, modern ladles contain refractories which are more resistant to chemical corrosion, particularly at the *slagline*, as well as to thermomechanical and mechanical wear. Demands for cleaner, inclusion-free steels and extended campaign lives between lining repairs/replacements have led to an increased use of alumina, doloma and magnesia-based refractories and a decrease in the use of fireclays.

2.3.1 *Basic Linings*

This category includes doloma and magnesia-based refractories which are used in the production of clean inclusion-free steels. They are available in carbon bonded, pitch bonded and ceramic bonded (fired) forms.

Carbon and pitch bonded forms are highly resistant to thermal shock. Low carbon types (<5% carbon) tend to be used in ladle bottoms and *striker pads* where mechanical erosion from the tapping stream is highest. Higher carbon types (5-15% carbon) are used in the wall, because of their resistance to chemical and physical attack from slag. However, the carbon in this type of refractory can burn in an oxidising atmosphere. Therefore, it is cost effective to keep these ladles in use (ie transporting steel) as much as possible, and to minimise the time spent at the ladle heating stations where the lining can burn. Pitch bonded types are less stable than carbon bonded forms and can produce fumes on initial heating.

Ceramic bonded forms tend to be less resistant to chemical attack and thermal shock than carbon bonded types. They also have relatively high coefficients of thermal expansion and so, to avoid thermal shock damage, heating from cold should be carried out at a rate less than 100°C/h. Once hot, the linings need to be kept hot (> 1,000°C) to avoid shrinkage (which can cause mechanical instability in the lining structure) and thermal shock damage. These guidelines can help the linings achieve twice the life of an equivalent alumino-silicate refractory.

Basic linings are usually dry bricked without cement jointing so less initial heating is required; however, care should be taken that the safety and back-up linings are properly dried before service. Heating rates of up to 1,200°C/h can be applied to carbon bonded types without excessive refractory wear.

In general, the thermal conductivity of basic linings tends to be higher than alumino-silicate linings, giving them greater heat storage capacity. This can produce improved ladle heating efficiencies but can also lead to higher steel and ladle shell temperature losses.

2.3.2 *Alumino-Silicate Linings*

These linings, which vary from 70% to 30% alumina are generally cheaper than basic refractories, but are more susceptible to chemical and mechanical wear. This makes them less suitable for the manufacture of ultra-clean steels which require secondary steelmaking treatment.

On the other hand, alumino-silicate linings are considered to be more tolerant of thermal cycling because they have a lower coefficient of thermal expansion, and are thus less susceptible to structural instability and thermal shock on cooling than ceramic bonded basic linings.

The linings are constructed with a cement jointing which must be dried prior to ladle use. Pre-heating temperatures in excess of 1,000°C should be avoided due to an increased rate of refractory deterioration.

3. DESCRIPTION OF LADLE HEATING SYSTEMS

3.1 Basic Small Ladle Heating Units

For small ladles, with less than 10 t capacity (such as those often used in foundries), ladle heating is often carried out with very basic combustion equipment. This usually consists of a retention head type gas burner placed inside the rim of the ladle, firing vertically downwards (Fig 1). Natural gas is mixed with air in the correct ratio using an air blast injector proportioning valve. When ladles without hoods are used, the heat from the flame and the ladle escapes to the atmosphere. Cold air is also drawn into the flame jet, which tends to cool the flame.

Fig 1 Small ladle heating station

The energy consumption of these systems is notoriously poor and in some cases heating a cold ladle produces efficiencies of less than 10%.

A substantial improvement can be made by fitting a refractory hood or a cover, to reduce both heat losses and induced cold air. The burner can either be built into the cover or an orifice can be left to allow the burner to be inserted. A sufficient gap around the hood or a suitable flue is required, to allow the combustion products to escape and prevent over pressurising the ladle. Any gap should be kept to a minimum.

Further energy savings can be made by controlling the ladle temperature. This can be achieved using a thermocouple temperature sensor inserted through the hood, which acts as a feed back control to the air flow valve and controls the firing rate of the burner. In this way, excessive ladle heating beyond the required temperatures can be prevented.

A case history at North British Steel, in which a 59% improvement in efficiency was achieved by adopting these techniques, is described in Section 5.

3.2 Conventional Cold Air Large Ladle Heaters

This section describes ladle heating in basic oxygen or electric arc furnace steel making shops, using large ladles, sometimes in excess of 100 t capacity.

3.2.1 *General Arrangement*

Most ladle heating installations use a burner built into a hood or lid, firing either vertically or horizontally into the ladle. In most cases, a thermocouple is inserted through the hood for temperature measurement and, in some cases, this is also used for temperature control. Fig 2 shows a schematic arrangement of typical ladle heating stations.

The hood reduces heat losses to the atmosphere and increases hot gas recirculation within the ladle. Without an adequate cover, the hot gases in the ladle escape to the atmosphere and cold air is drawn into the flame jet. By restricting gas escape, a hood also helps to pressurise the ladle.

3.2.2 *Burner Sizing*

To ensure that required heating rates are achieved at optimum efficiency, correctly sized burners must be used. Problems can occur with both undersized and oversized burners as follows:

Undersized:

- Cannot achieve required heating rates.
- Cannot achieve maximum temperatures.
- Provide insufficient gas input to pressurise the ladle and avoid air ingress on horizontal stations.

Oversized:

- Heating rates and maximum temperatures are achieved at a fraction of the full fire-rate, which may reduce gas velocities and limit flame penetration and gas circulation.
- Failure of the temperature controls can lead to gross overheating which can produce severe damage to refractories, burner hoods and combustion equipment.

Whilst there is virtually no advantage in undersizing a burner, oversizing can reduce noise levels, because the burner operates on a reduced fire-rate, and very rapid heating rates can be applied if required, for example when a cool ladle is put into service at short notice. It is generally favourable to oversize rather than to undersize, but the greater the difference from that required, the more the problems that are possible.

To evaluate the correct burner size, experts with burner sizing experience should ideally be consulted, who will consider the following guidelines.

- The burner should be sized to allow the maximum heating rates and maximum temperatures to be achieved. As described in Section 2, these depend upon the refractory composition which may restrict the heating rate and, together with melting shop practices, will determine the maximum desirable operating temperature. Advice on the refractory heating requirements should be obtained from the refractory supplier or from refractory specialists.
- When a suitable temperature/time relationship has been defined, a mathematical modelling exercise should be carried out to determine the incremental quantities of heat which will be transmitted to the brickwork and shell, including losses, when the refractory arrangement is subjected to the defined heating cycle. Technical experts are required for this evaluation. The maximum incremental quantity will then be used as an initial assessment of the maximum burner requirement (H_R(GJ/h)).

The burner fuel requirement H_f (GJ/h) can be defined by:

$$\boxed{H_f = \frac{H_R}{\mu}} \qquad \ldots (1)$$

where μ is the efficiency of the ladle heating.

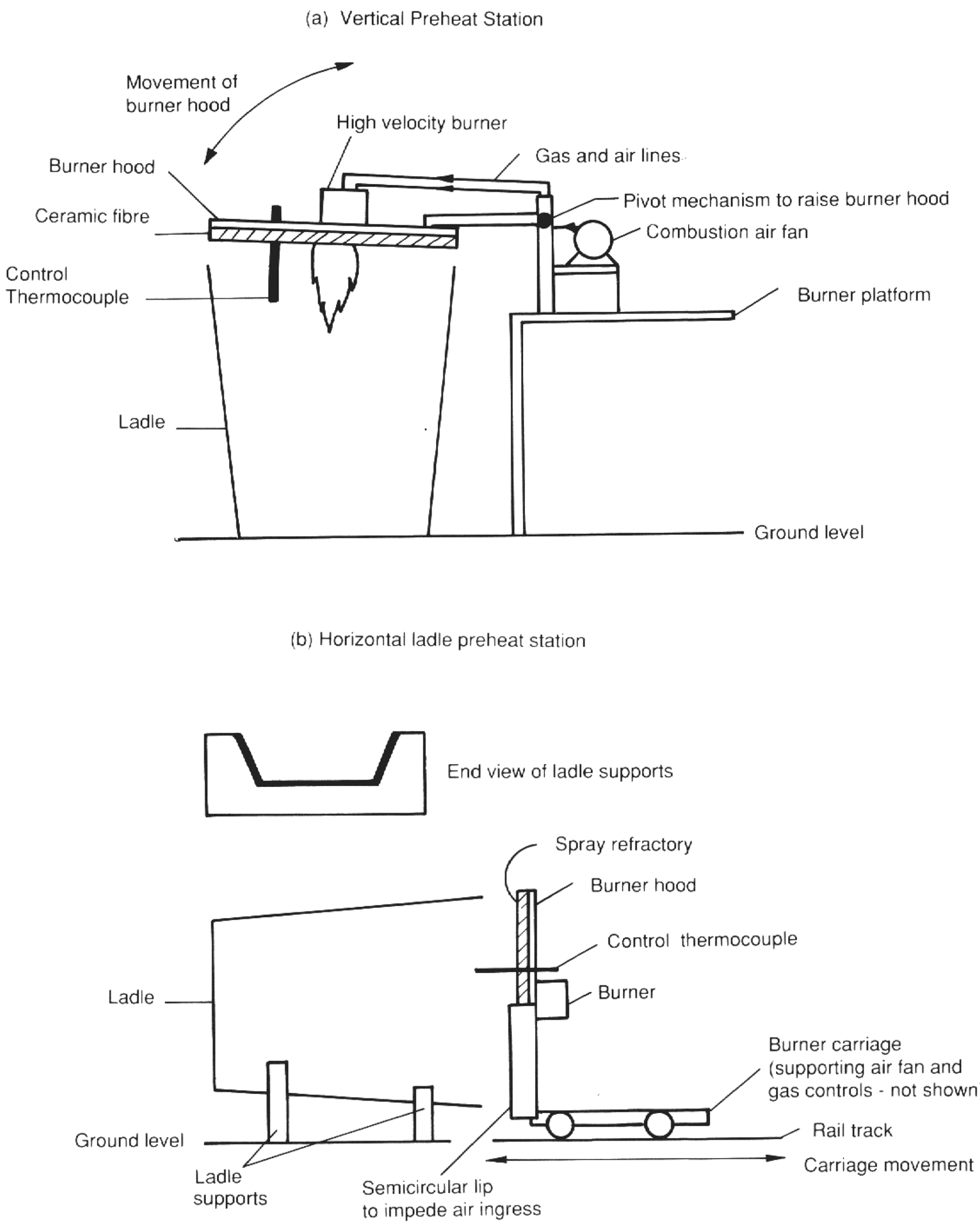


Fig 2 Typical ladle heating stations

As stated in Section 2.2 (Energy Efficiency), the efficiency depends upon the design of the heating unit and temperature of operation. Examples of the range of efficiencies are given in Table 1, which also demonstrates the benefits of using heat recovery techniques to pre-heat combustion air (Section 3.3), and highlights the detrimental effects of cold air ingress into the ladle.

Efficiency values of 35, 51 and 68% are typical for cold air, recuperative and regenerative burners respectively, for operation at 1,100°C and 5% oxygen in the ladle gases. With the excess air level increased to 80%, perhaps due to ingress into the ladle, cold air burner efficiency is reduced to 15%. These figures can be used to estimate burner size; however, for details of efficiency at intermediate conditions technical experts should be consulted. When burner sizing it is quite usual to add a 20% safety factor to the value of Hf, to allow for possible variations in efficiency and also because overrating is preferable to underrating.

Table 1 Ladle heating efficiencies

Ladle exhaust gas temperature °C	Combustion air temperature °C	Oxygen content ladle gases (% dry basis)	Ladle heating efficiency %
800*	Cold	5 (= 27% excess air)	51
900*	Cold	5	45
1,100**	Cold	5	35
1,100**	400 (Recuperator or SRB)	5	51
1,100**	800 (Regenerative ceramic burner)	5	68
1,100**	Cold	10 (= 80% excess air)	15

* Typical average ladle gas temperatures when heating to aim for temperatures between 1,000 and 1,200°C

** Typical instantaneous values with the ladle held at 1,100°C

Whilst there is always a danger in using short cut methods for sizing purposes, an approximation method, described in Appendix 2, can be used to check whether the burner sizes proposed are compatible with the specification. It should not be used for burner design, since it assumes that the desired ladle condition is achievable in a certain time. This depends upon the refractory conductivity, and the heating times can be verified only with the mathematical modelling techniques mentioned above.

3.2.3 *Burner Selection*

A vast range of burner types are used for ladle heating and it is beyond the scope of this guide to discuss the range available. Specific enquiries should be directed to combustion equipment suppliers, some of which are listed in Appendix 3.

Burner selection will depend upon the fuels available at the plant. Fuel oils burn with a highly luminous flame which may enhance radiant heat transfer, but may have other fuel handling disadvantages. Gas-fired installations are most common and in general the burner performs well over a wide range of excess air levels with a turn down ratio of about 5:1.

Heating the ladle base is critical to effective operation and it is therefore essential that burner velocities are adequate. In most cases both high and medium velocity burners can be used, and the relative merits are discussed below.

High Velocity Burners

High velocity burners produce gas velocities of approximately150 m/s with a *quarl* pressure of about 12.5 mbar gauge. They are fast mixing burners which produce a short high velocity flame, which reduces the likelihood of flame impingement on the refractory, yet maintains sufficient momentum for good penetration. On the other hand, high velocity burners can be noisy and cold air can be drawn into the flame. This can be avoided on vertical stations by using correctly positioned lids, and on horizontal stations by reducing the gap between the hood and the ladle rim. Provided that the drawing in of cold air can be avoided, the flame characteristics can be beneficial to gas circulation and temperature uniformity.

Medium Velocity Burners

Medium velocity burners produce gas velocities between 50 and 100 m/s, with quarl pressures of 5 mbar gauge. They are less noisy than high velocity burners and are less likely to draw in cold air. The flame may be long and care is needed to prevent flame impingement on the refractory. The burners operate with lower air and gas supply pressures than high velocity burners and thus have a lower combustion fan energy requirement. However, the burners are more susceptible to back pressure problems than high velocity burners.

3.2.4 *Horizontal versus Vertical Stations*

To prevent refractory bricks from falling out, newly bricked cold ladles need to be heated on vertical stations - only when the bricks have been thermally expanded can the ladle be laid horizontally without brick fall out. The temperature at which the ladle achieves structural stability varies according to the brick type and the method of construction. In general, it is considered safe to tilt a new ladle after heating the refractory to about 800°C. Thereafter, provided the ladle is kept reasonably hot, horizontal heating can be applied.

The relative merits of horizontal and vertical heating are described below.

Horizontal	**Vertical**
Relatively easy to install, heavy equipment can be supported on the ground or on rail carriages (bogies).	Unless detached hoods are used, hood mechanisms are required which may be expensive, especially with heavy equipment.
Good access for maintaining refractory hood and combustion equipment.	Poor hood and combustion equipment access, except with detachable hoods.
Teeming valve maintenance can be carried out in pre-heating position.	*Teeming* valve needs to be changed at another location.
Less susceptible to flame penetration damage.	*Buoyancy* effects work against flame penetration.
Hood refractories less susceptible to damage.	Movement of hood mechanisms and greater exposure to hot ladle gases can increase hood refractory damage.

Problems of air ingress caused by negative pressure on the lower lip (due to *buoyancy* on upper lip) can occur, especially with heat recovery systems where gases are ducted through the ladle hoods. Air ingress can be reduced by a good seal between the burner hood and the rim, but this may be difficult to maintain.	No problems from *buoyancy*.
Air ingress can occur because of the drawing in effects of high velocity flames. This can be remedied by a reduced gap between hood and rim.	Air ingress eliminated by correct positioning of hood.

Using detachable hoods on vertical stations eliminates the need for expensive structural supports and hood lifting gear. It is usual in such cases to provide an off-ground support to allow access for hood refractory and combustion equipment maintenance, and therefore a larger space is required. The main disadvantage of detachable hoods is the requirement for a crane to move the burner and hoods, and the potential for damage in such manoeuvres. If care is taken and space is available, detachable hoods can operate effectively.

Significant energy benefits can be gained by firing upwards at a suitable angle, although current stations do not operate this practice.

The main problems that need to be overcome are:

- avoiding brick fall out;
- avoiding damage to burners from falling slags/*skulls*;
- crane handling.

The possible advantages are:

- increased heat to ladle base;
- air ingress from *buoyancy* would be reduced and heat recovery could be applied more effectively;
- gate valve access - steps may be required to provide access;
- hood mechanisms are simplified by mounting on ground.

Clearly, this method would not be suitable for heating cold ladles, due to structural instability.

3.2.5 *Air Ingress*

Table 1 demonstrates that the ingress of cold air into a ladle (for example 80% excess air) is detrimental to ladle heating efficiency and care should be taken to prevent this effect.

On horizontal stations, air ingress can occur by the flame jet drawing in air and by *buoyancy* effects. Some gas flow patterns that can occur on horizontal ladle heaters with cold air high velocity burners are shown in Fig 3.

Fig 3(a) demonstrates that without a hood, both *buoyancy* and flame jet intake give rise to air ingress. For this reason, and because of wasteful radiation losses, this arrangement is not recommended.

Fig 3(b) shows the classic chimney effect where gases, driven by the *buoyancy* of the hot gas column between the hood and the ladle rim, escape from the upper rim causing cold air to be induced at the lower rim. This occurs because the static pressure at the lower ladle rim is insufficient to overcome the *buoyancy* effect. With lower velocity flames air ingress and *buoyancy* can deflect the flame upwards, reducing the penetration to the base.

The pressurisation of the ladle depends upon the burner firing-rate and the area available for gases to escape at the ladle rim. As the gap between the ladle rim and the hood is reduced, the ladle pressurises sufficiently to prevent air ingress at the lower rim. This is shown in **Fig 3(c)**.

For cold air burner systems the gap between the ladle rim and the hood is the only available route for exhaust gases to escape; hence the pressurised condition is relatively easy to achieve provided that an adequate burner size has been installed.

An equation has been derived for cold air burners which approximates the relationship between the actual flow of hot gases from the burner into the ladle Q (m^3/s), the ladle diameter D (m), and the gap size x (m) which would prevent air ingress:

$$\boxed{Q > Dx \sqrt{\frac{\pi}{2} \; Dg \; \left(\frac{T}{288} - 1\right)}} \qquad \ldots (2)$$

where T = gas temperature (K), g = 9.81 m/s^2

Q is dependent upon the fuel type, the burner firing-rate, the excess air level and the gas temperature. A worked example is shown in Appendix 4. It should be noted that the gap size, x, is the critical parameter and should be minimised whenever possible. To achieve zero ingress with a large gap size requires a very high burner rating. Therefore, in cases where a seal is difficult to attain, it may be prudent to use vertical stations.

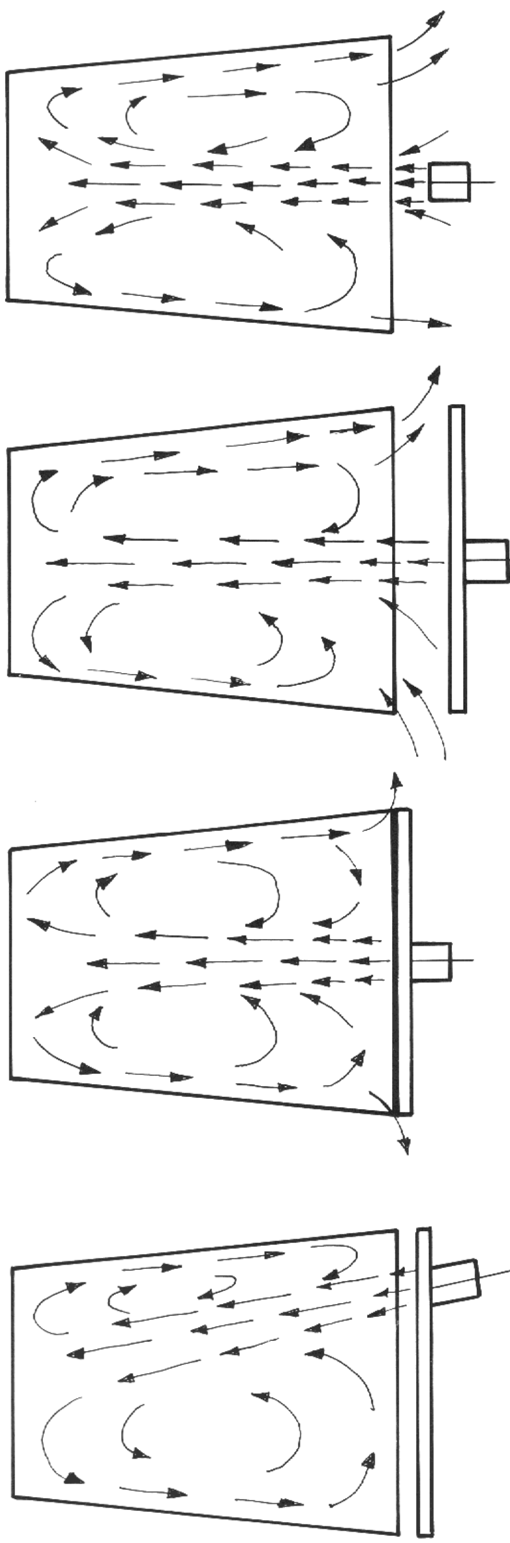
For systems using heat recovery, up to 90% of the ladle gases may be drawn through a duct in the hood to a recuperator. In this case a good, if not perfect, seal between the hood and the rim must be achieved. This can be limited by *skull* on the ladle rim and associated difficulties, as discussed in Section 3.3.

Fig 3(d) shows a case where the high velocity burner has been eccentrically placed in the upper half of the hood and angled down. This draws in gases at the upper rim, preventing the *buoyancy* effect. However, oversizing or incorrect positioning of the burner can cause air intake at the upper rim, and also the burner needs to be angled carefully to avoid flame impingement on the refractories. Generally, preventing air ingress by minimising the gap is preferred over using eccentric burner positioning.

In vertical pre-heat stations the chimney effect is avoided, and with a well fitting hood air intake is reduced.

3.2.6 *Back Pressure Problems*

Care must be taken to ensure that reducing the gap does not produce a pressure build up in the ladle, causing back pressure problems with the burner. The optimum case is the minimum gap which does not affect burner operation. Minimising the gap also reduces radiation losses.



(a) No hood, ingress due to flame jet intake and buoyancy.

(b) Hood, large gap. Ingress due to buoyancy and, to a lesser extent, jet intake.

(c) Hood, good seal. Ladle pressurised. Ideal case unless back pressure affects burner operation.

(d) Top fired, angled down. Tends to intake air at upper rim. Reduces buoyancy effect.

Fig 3 Gas flow patterns on horizontal stations with cold air high velocity burners

An approximate relationship between the ladle pressure P (mbar), generated by a cold air burner firing with stoichiometric air at a rate of F (GJ/h), assuming no ingress due to *buoyancy*, is given as:

$$P = 5.854 \times 10^{-8}\ T \left[\frac{F}{Dx}\right]^2 \qquad \ldots (3)$$

where T = gas temperature (K)
D = ladle diameter
x = gap size

Worked examples using this equation are given in Appendix 5. It should be noted that for a burner with a 5:1 turn down, low fire pressure will be 25 times less than that at high fire. Alternatively if the gap size is doubled, pressure will drop by a factor of 4.

Burners which operate with a set gap to avoid back pressure problems, can suffer from low ladle pressure when the burner turns down. In these cases, gases could be ducted through the hood to atmosphere, using a damper or vent with a counterweighted flap, to control ladle pressure whilst operating with a minimum gap/seal between the hood and the rim. This would also eliminate radiation losses which occur through the gap.

3.2.7 *Ladle Temperature Measurements*

Internal

Internal temperatures can be measured by inserting a sheathed thermocouple through the burner hood or lid. The sheath is necessary to reduce corrosive attack from combustion products and, in the horizontal position, the sheath will also provide mechanical strength to prevent the thermocouple from drooping.

In order to select the best thermocouple type it is recommended that instrument suppliers be consulted, but in general Chromel/Alumel types can be used for temperatures up to 1,100°C. More expensive thermocouples such as Platinum/Rhodium types are suitable for accurate measurement at higher temperatures but, because ladle heating equipment is often subjected to mechanical damage from impact, this may not be cost effective.

A thermocouple placed through the hood will record the temperatures surrounding the thermocouple. Thus, with a minimal gap between hood and rim, the thermocouple indicates an average of the temperatures within the ladle. This is generally considered to be a valid measure of average ladle temperature.

The greater the gap the less accurately the thermocouple will represent the ladle temperature. Generally, the deeper the thermocouple is inserted into the ladle, the more accurate the ladle temperature measurement will be, but the thermocouple will then be more vulnerable to mechanical damage from movement of the ladle or the hood.

As an alternative, infrared sensors can be used to measure temperatures of the hot face of the ladle refractory. This method provides a more accurate measure at a specific position in the ladle, and can be used irrespective of the gap between the hood and ladle.

In order to view the ladle refractory through a flame, or where the flame radiation can interfere with the signal, a 3.9 μm infrared temperature sensor can be used to indicate the refractory wall temperature.

Work has been carried out at BS Stainless (now Avesta, Sheffield) and Rotherham Engineering Steels to determine the potential benefits of the various methods of temperature measurement. Infrared sensors have the advantage that the refractory temperature can be measured independently of other factors (ie hood position). Thus, when pointed at the coolest part of the refractory, usually the base, the measurement indicates when a ladle is ready for use. However, if slag or a hot metal *skull* is left in view of the sensor, inaccurate temperatures are measured or, if viewed through the hood, loose refractory or ceramic fibre can interfere with the measurement. Either way, care and good maintenance is required to avoid problems when using infrared sensors.

On the other hand, thermocouples are considerably cheaper and are less susceptible to interference from slags, *skulls* or damaged refractories. Also, if a small gap can be achieved between the rim and the hood, little, if any, temperature difference would be detected between a thermocouple and an infrared temperature sensor. Therefore, in cases where ladle and hood can be brought into reasonably good contact, a thermocouple temperature measurement will suffice.

External (Shell)

Ladle shell temperatures can be measured using hand-held contact temperature sensors (e.g. thermocouples) or portable infrared temperature sensors. Shell temperatures can help determine equilibrium ladle drying and pre-heat soaking times.

When shell temperatures are steady, the ladle is likely to be approaching a state of thermal equilibrium; ie the rate of heat input by the burner equals the rate of energy lost by the shell and waste gases combined, and the heat stored in the bricks is not increasing. Ideally, the ladle should reach this condition when it is required for use. Prolonged heating in this condition is wasteful and indicates that the ladle was placed on the heating station earlier than was necessary.

External temperature measurements are important during trials to establish the optimum ladle heating cycles required for adequate operation. External measurements can also indicate hot spots where the refractory lining may be wearing thin, and it can assist in detecting potential areas for breakouts or the need for refractory repairs. Thermographic techniques, which make use of infrared imagery, can be useful in this application.

3.2.8 *Temperature Controls*

Internal ladle temperature sensors are often used to feed signals to automatic programmable temperature controlling devices, which vary the burner firing-rate according to the control settings. Such devices can be used to:

- maintain various temperature ramps (°C/h) to suit the heating rates of certain refractory types;
- hold the ladle at temperature for a specified period to allow time for changes in the refractory material or drying to take place;
- hold at a maximum temperature to avoid overheating the ladle.

Without temperature controls, damage to the ladle refractories can occur and energy can be wasted by overheating. Furthermore, excessive heating can damage the combustion equipment and the refractory hoods.

Automatic temperature controls are strongly recommended to save fuel and to ensure effective operation.

3.2.9 *Burner Controls*

Temperature controllers adjust the burner firing-rate according to the control temperature settings. Burners can operate with either full *modulation control*, high/low fire operation or on/off *(impulse) control.*

Air/fuel ratio is maintained at efficient levels over the firing range by suitable combustion controls. There are many methods of control with varying levels of cost and sophistication. Some typical combustion controls include:

- premix burner controls, for *premix* burners;
- simple impulse regulation systems (Pressure Divider Technique);
- simple *ganged valve* assemblies;
- multiplying regulator systems (particularly for systems with air pre-heat);
- electronic ratio controllers.

Fig 4 shows the general arrangement for these control types. Details of the relative merits of each system are beyond the scope of this guide[2]: for advice on a particular application, it is suggested that a combustion engineer should be consulted. Combustion systems should be well maintained and checked regularly because failure to operate with the correct air/fuel ratio can severely affect ladle heating efficiency.

Although impulse firing methods have found applications in furnace heating, they have not been used in ladle heating. They offer the advantage that burners are operated either on full-fire or off, ensuring maximum penetration to the base with minimum possible air ingress.

3.3 Combustion Systems with Waste Heat Recovery

3.3.1 *Examples of Waste Heat Recovery*

It is possible to improve the ladle heating efficiency substantially by using heat from the hot ladle exhaust gases to pre-heat combustion air. The improvement in efficiency is directly proportional to the air pre-heat temperatures that can be attained, and this varies according to the type of heat recovery equipment used. There have been three main types of waste heat recovery systems used on ladle heating stations.

- Recuperator systems in which ladle gases are ducted through the lid to an external recuperator, exchanging heat with the combustion air.
- Self-recuperative burner (SRB) systems in which ladle gases are flued through an annular counter-current heat exchanger built within the burner assembly, which transfers heat to the combustion air (Fig 5).
- Regenerative ceramic burner (RCB) or Integral Bed Burner (IBB) systems in which a pair of twin burners fire and exhaust alternately. Exhaust gases pass through the non-firing burner and into a ceramic regenerator (Fig 6) where heat is released and stored. On reversal, combustion air passes through the regenerator whilst the other burner exhausts.

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[2] Refer to 'Gas Controls', British Gas School of Fuel Management.

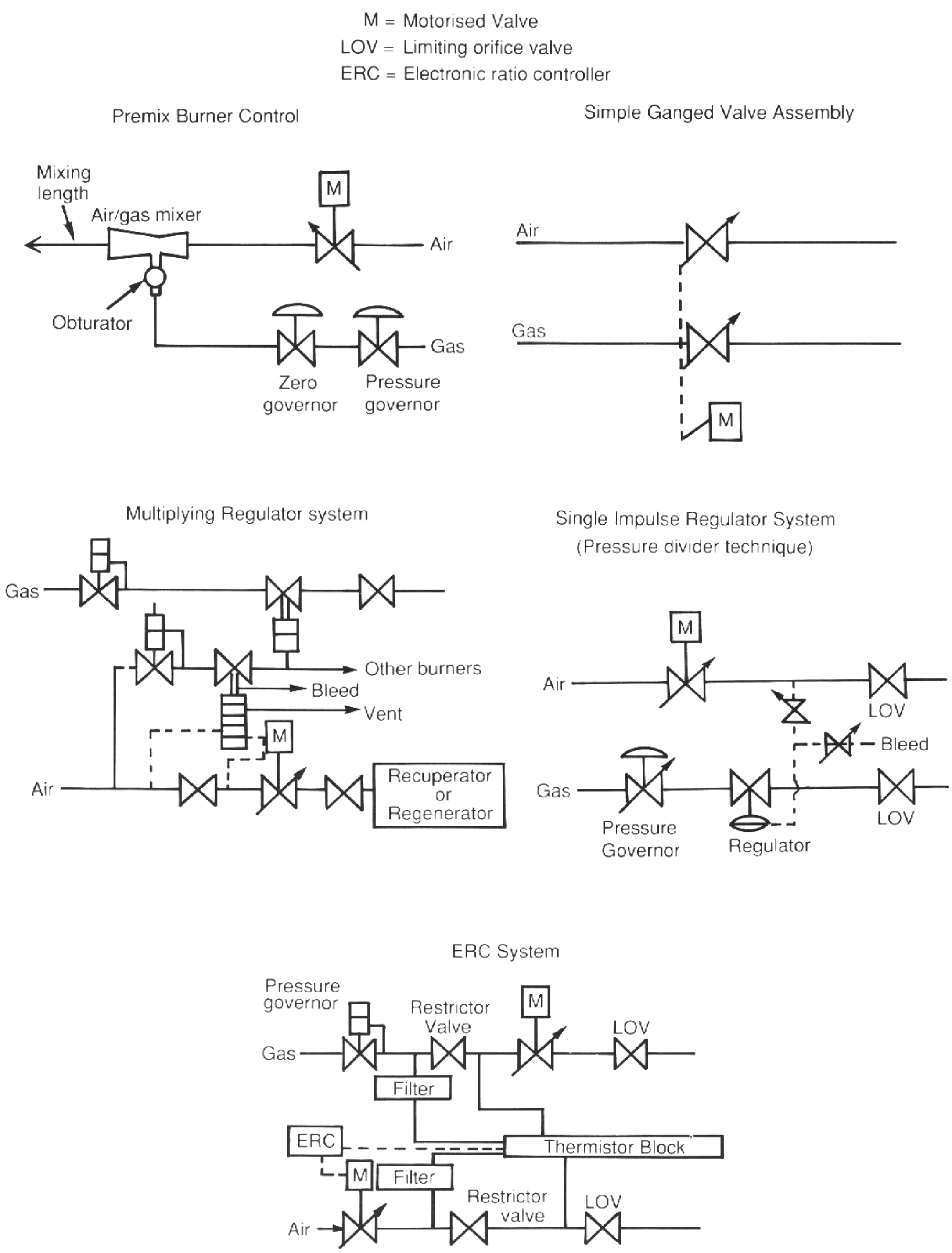


Fig 4 Air/fuel ratio controls

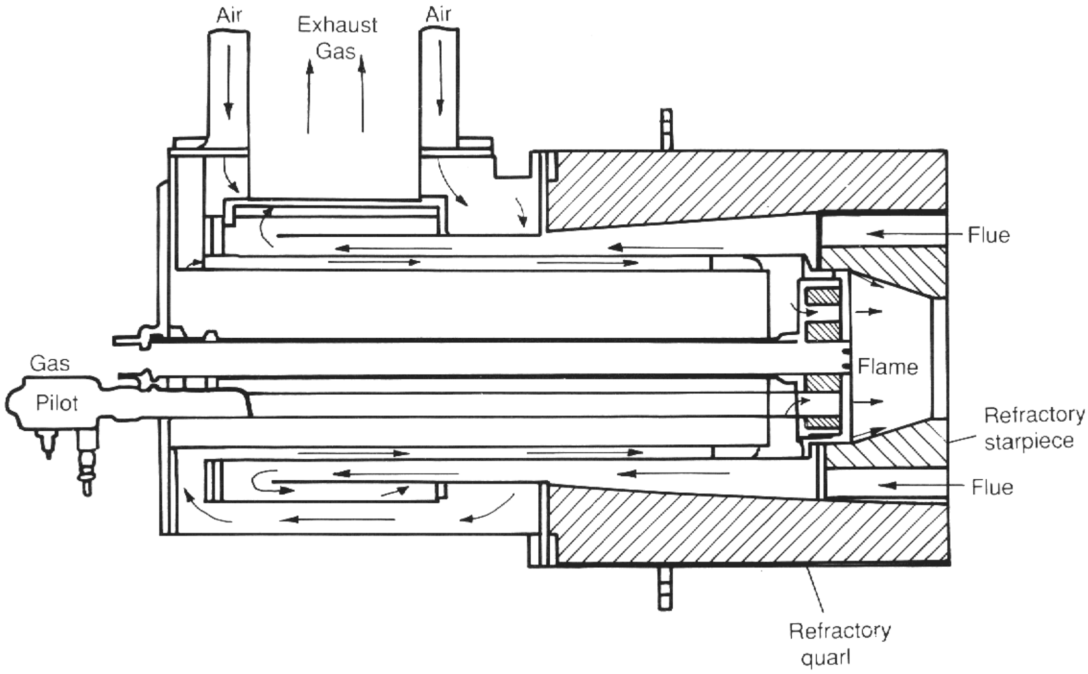


Fig 5 Cross section of a self-recuperative burner

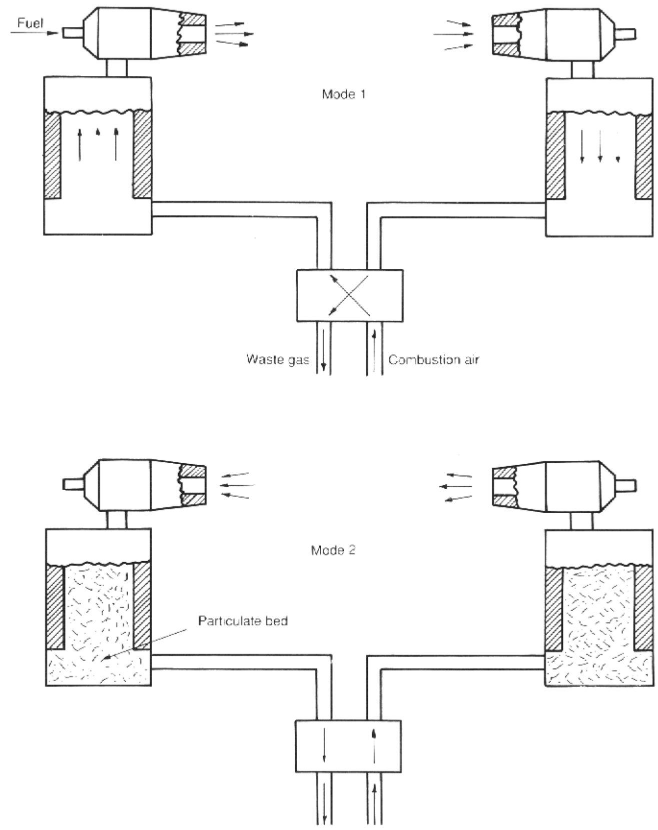


Fig 6 Firing with regenerative burners

Each of these systems has been used extensively on reheating furnaces and, with the exception of the IBB which is in earlier stages of application, the technology is well proven in this area. Compared with a cold air combustion system, with a furnace operating at 1,000°C, a fuel saving of up to 25% could be expected from using either an external recuperator or an extended flue SRB system, and a fuel saving of up to 40% could be expected from an RCB system. The difference in savings is due to the increased levels of air pre-heat which are attainable with the RCB system (see Table 1).

In contrast, there have been a limited number of applications on ladle heating stations, partly due to the problems of evaluating payback periods with limited fuel metering, and partly due to less predictable burner performance in the unsteady state conditions of ladle heating. Owing to the novelty of such systems and the associated risk of applying new technology, three projects were given assistance by the EEO in order to quantify the energy benefits. These projects are described in Section 5.

Problems with air ingress and burner/exhaust port positioning reduced the expected efficiencies of the three installations, and this was compounded by inadequate burner sizing in some circumstances. However, energy savings were achieved when the problems were minimised. Full benefits could be realised from waste heat recovery systems by minimising the gap between the hood and rim and achieving a good seal (see below) and using correct burner sizes (see Section 3.2.2).

A vertically fired RCB system using a 4.3/5.8 GJ/h burner has been used successfully on newly bricked 70 t ladles on a steel plant in Italy. The system, fired by natural gas, was reported to have a ladle heating efficiency of 65% and had the additional benefit that with ladle gases passing through the regenerator bed, pitch tar fume emissions into the workshop were reduced. The build up of pitch tar in the beds caused no operational problems providing that the ceramic balls in the bed were washed annually. The system heats new dolomite/alumino-silicate linings to 1,100°C at a rate of 140°C per hour. On reaching the set point, burner fire-rates are turned down with full *modulation control*. The system uses a pivoting hood lined with ceramic fibre modules as illustrated in Figs 7 and 8.

Another plant in Italy uses two horizontal stations heating 40 t ladles, one equipped with a 2.1/2.7 GJ/h RCB system, the other with a 2.1 GJ/h SRB. The RCB system is used to heat new ladles to 1,200°C after initial heating on a conventional vertical station to over 600°C. The SRB is used in the melting shop to maintain temperature in working ladles. Each station uses ceramic fibre lined hoods. To achieve a good seal on the SRB station, used ladles are cleaned manually ensuring that all *skulls* are removed prior to ladle heating. The hood has a protruding fibre-lined contact rim which fits flush to the ladle. Although no efficiency data are available on these systems, the plant operators report that major fuel savings have been achieved. The systems are illustrated in Figs 9 and 10.

Each of these examples demonstrates that heat recovery systems can be used effectively, either on stations for newly bricked ladles or on used ladles providing that care is taken to ensure that ladle rims are kept clean prior to heating. A vertically fired SRB station was used at the now closed British Steel Tinsley Park Works and, although no performance data are available, reports indicate that the system achieved the expected ladle heating efficiency without operational problems.

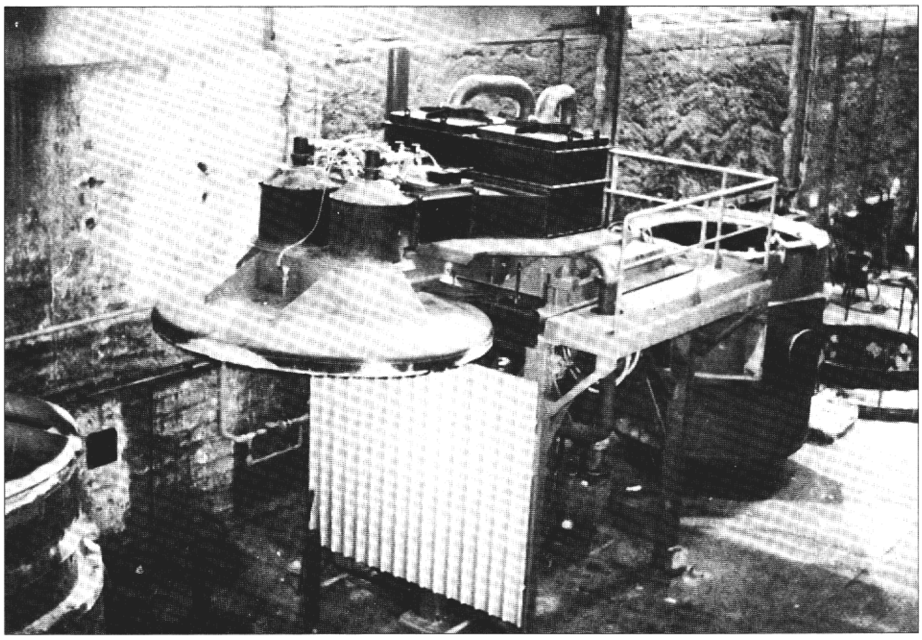


Fig 7 Vertically fired RCB

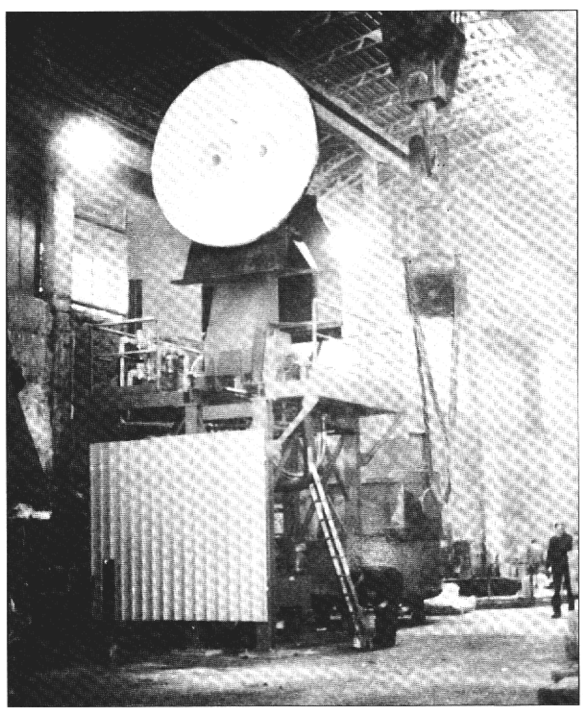


Fig 8 Vertically fired RCB with hood in a raised position

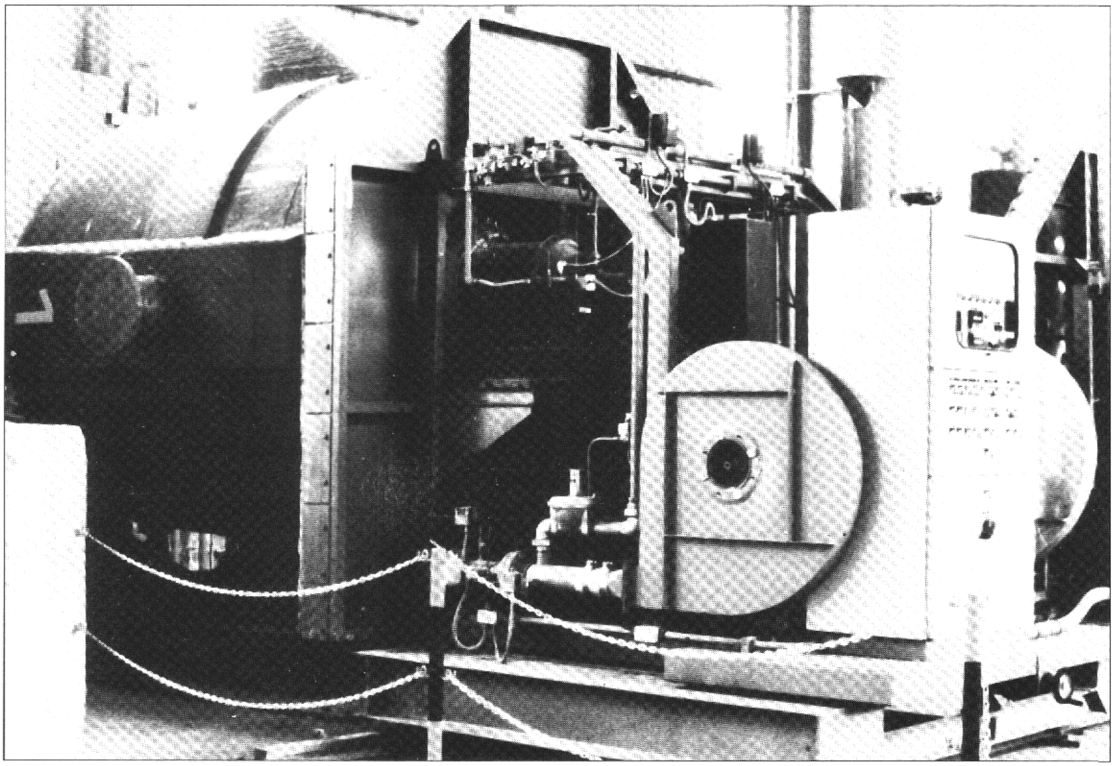


Fig 9 Horizontal RCB

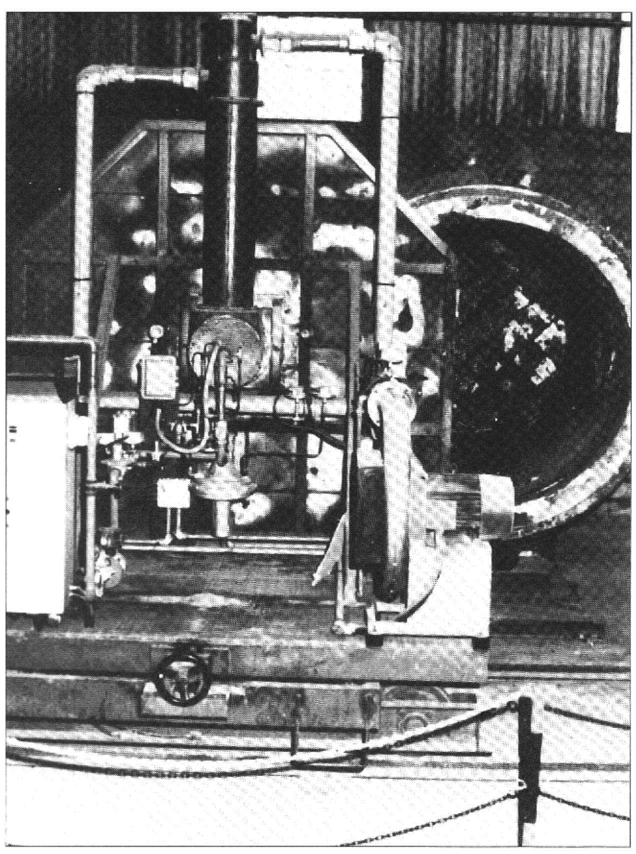


Fig 10 Horizontal SRB

3.3.2 *Good Seal Requirements*

In order to ensure maximum operating efficiency when using heat recovery (see Section 5) it is essential to achieve a good seal between the ladle rim and the burner hood. Several suggestions to assist with this are listed below:

- *Skulling* (the build up of steel in the ladle rim) will result in an uneven contact surface for the joint with the burner hood. To prevent this, the ladle rims should be kept clean by diligently removing any build-up and/or by preventing a build-up in the first place. Care should be taken to avoid damage to refractories during cleaning. *Skulling* resulting from Electric Arc Furnace tapping spout drips can be avoided by the use of a refractory cover beneath the pouring spout (Fig 11). The device, called a lip protector, is in use at Templeborough Electric Melting Shop, UES, and is highly effective in keeping ladle rims clean.
- To allow a flush fit between the hood and the ladle rim, the burner hood should be at least equal in diameter to the ladle rim and should be lined with ceramic fibre modules. This allows a reasonably clean ladle rim to press into the lining, giving good contact. Again, this requires that ladle rims be kept clean. If *skulls* protrude, it will not be possible to form a press seal and furthermore the ceramic fibres will be damaged.

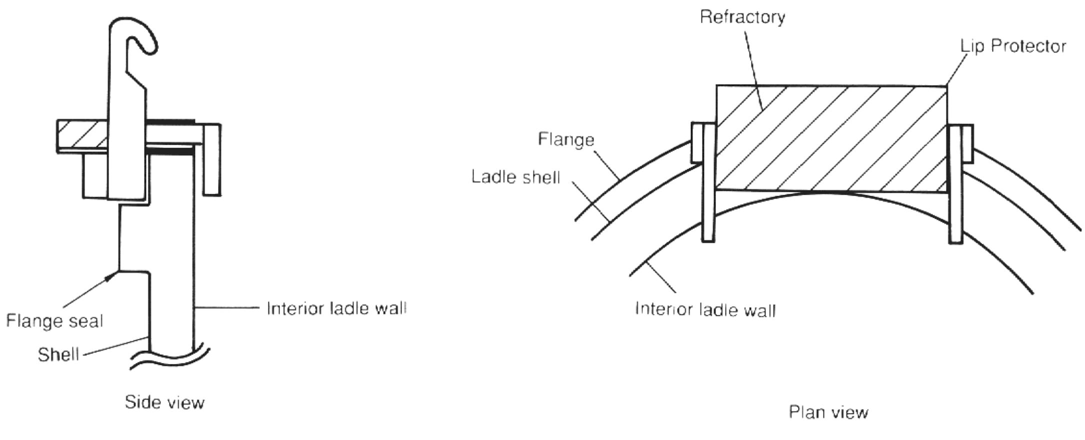


Fig 11 Ladle Lip Protector - to avoid *skull* build-up on rim

- The burner hood can be designed to prevent or reduce air ingress at the lower ladle rim. Several designs have been tried, all with varying degrees of success, some of which are shown in Fig 12. Nearly all the designs fail if the ladle rim is badly *skulled.*

Problems of air ingress with heat recovery systems are not usually encountered on vertical stations, therefore these stations should be given consideration when selecting systems with heat recovery.

3.3.3 *Burner Controls*

The pre-heating of combustion air can lead to increased air pressures on the combustion air supply line, and therefore it is recommended that the static air pressure, in isolation, should not be used in air-led impulse burner controls. It is preferable to use systems in which the impulse signal relates to the actual air flow; for example, pressure differentials across flow restrictions, such as orifice plates, or electronic ratio controlling devices. An example of a gas control and safety pipework system for an RCB installation is shown in Fig 13.

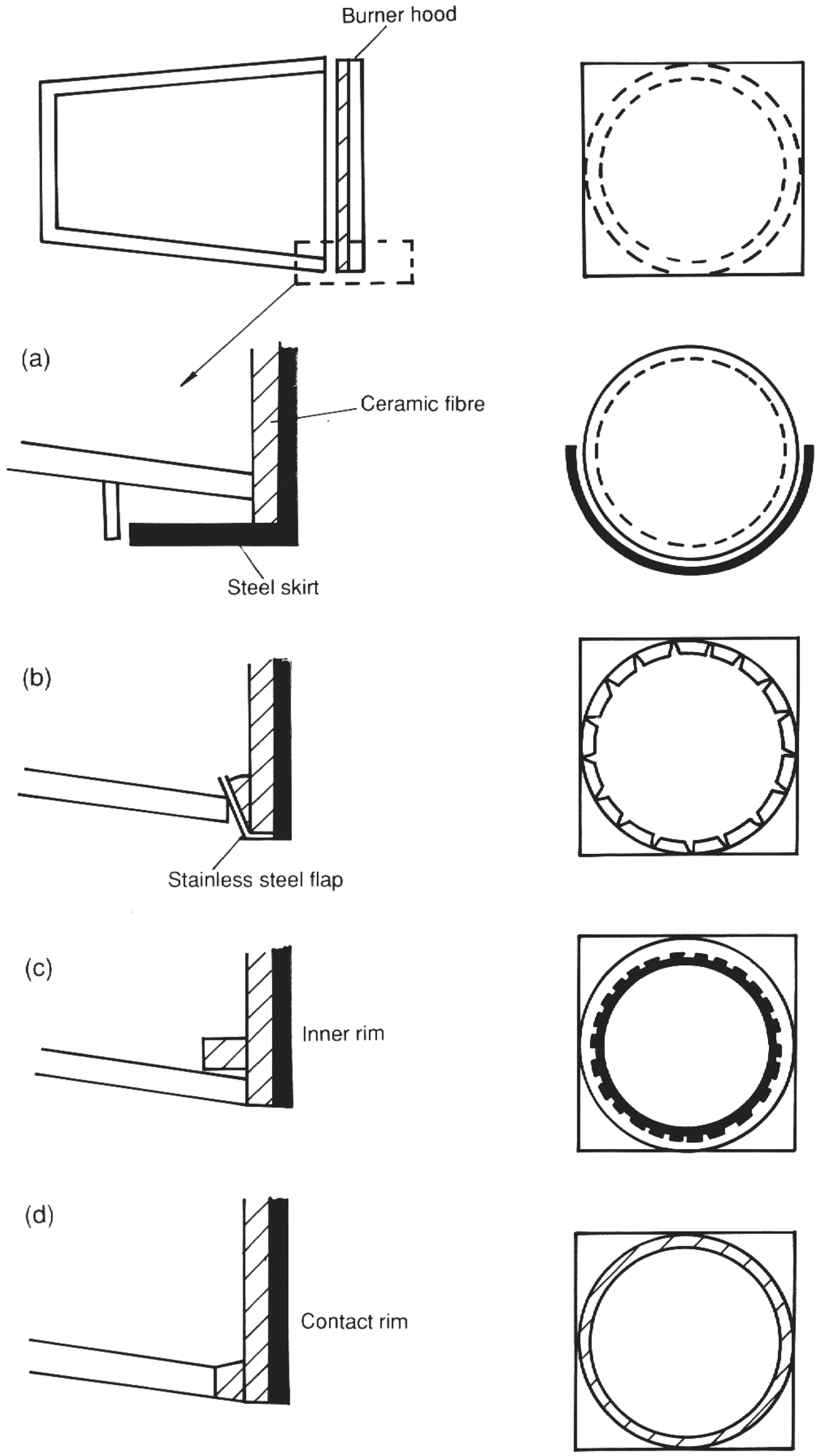


Fig 12 Designs attempting to seal burner hood and ladle rim on horizontal stations

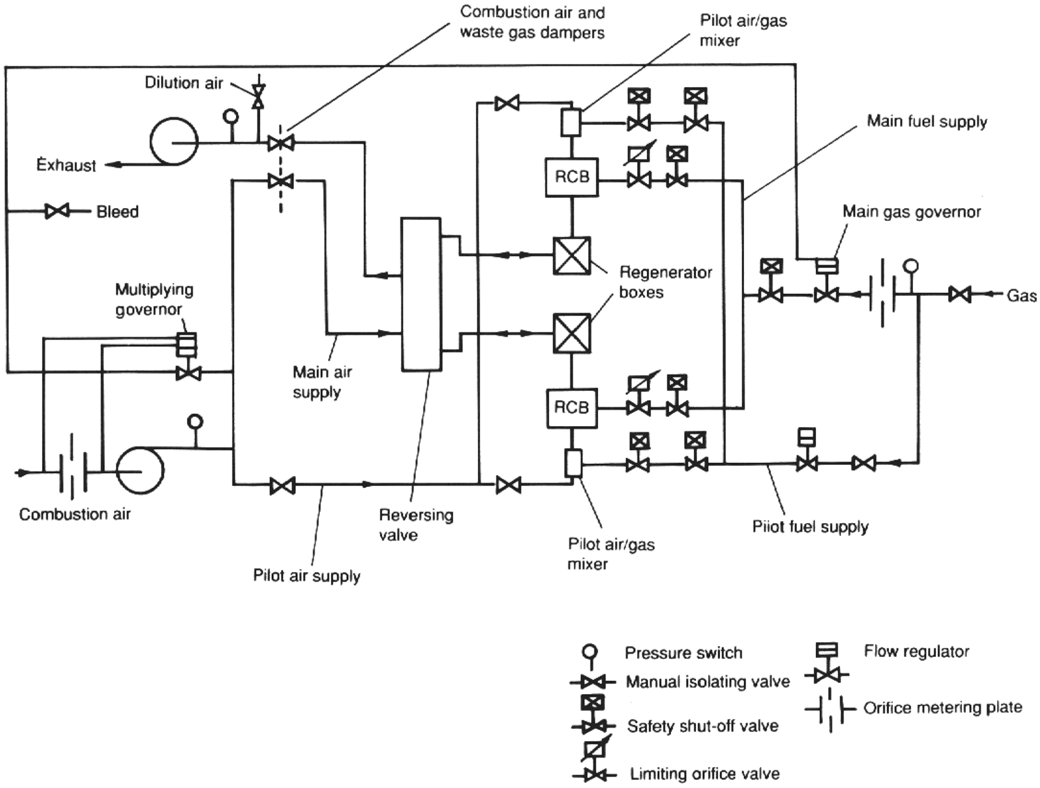


Fig 13 Schematic arrangement of regenerative burner pipework

3.4 Oxygen Enriched Burners

Oxygen-fuel and air-oxygen-fuel burners have been considered for use on ladle heating stations, particularly when higher refractory temperatures need to be achieved rapidly.

The viability of oxygen enrichment depends on many factors and so each case must be assessed individually. A case history at Sheerness Steel is described in Section 5, and the general considerations are discussed below.

Potential Advantages

The potential advantages of using oxygen enriched burners are:

- reduced fuel consumption;
- higher rate of heat transfer to the refractories;
- increased productivity due to lower yield losses and increased ladle availability.

Conventional air-fuel combustion results in waste gases with a significant nitrogen content, adding nothing to the combustion process, but absorbing energy in the waste gas. For example, the nitrogen in the waste products of air-natural gas mixtures consumes 26% of the gross energy content. Nitrogen waste gas losses can be reduced using oxygen enriched air, or eliminated using pure oxygen, in place of normal air in the combustion mixture, and this results in fuel savings.

Faster heating rates result from higher flame temperatures which increase the radiant component of heat transfer. In addition, the partial pressures of carbon dioxide and water vapour are increased proportionally, giving rise to higher emissivity of the combustion products and thus more efficient radiant heat transfer. The dissociation of combustion products which may occur at the higher flame temperature will also tend to effect flame emissivity, depending upon the extent of dissociation. Faster heating rates can reduce heating times, with subsequent fuel savings.

For some plants faster heating rates may reduce the time needed for pre-heating in the melting shop, thereby allowing productivity to be increased.

Disadvantages

The major disadvantages of using oxygen enriched burners are:

- the cost of supplying oxygen;
- increased NO_X pollution;
- low pressurisation of the vessel.

The cost of supplying oxygen to an enriched burner system should be evaluated critically during the economic assessment of a proposed installation.

To evaluate the point at which oxygen enrichment becomes cost effective for a 15 hour pre-heat, the following empirical criterion can be used:

$$\frac{\text{Cost of supplying oxygen per 100 m}^3\text{ (stp)}}{\text{Cost of natural gas per GJ}} < 1.5$$

It should be noted that this criterion assumes ladle heating to 1,100°C and does not include the benefits from reduced electrical energy consumption arising from reduced exhaust and combustion air requirements.

The higher flame temperature achievable with oxygen enriched combustion leads to increased levels of NO_X compared with those normally encountered with air-fuel burners. With the increasingly stringent guidelines for such pollution, this should be taken into consideration.

Although there may be energy savings at point of use from reduced fuel consumption, for a total picture the energy needed to produce the oxygen must also be taken into account, and the quantities of oxygen used must be balanced against the fuel saving.

The reduction in waste gas volumes from oxygen enriched burners will reduce ladle pressures, which could result in adverse air ingress. The maintenance of a good seal between rim and hood is therefore critical when using these burners.

3.5 Heating with Electric Elements (Indirect Resistance Heating)

Compared with combustion systems, electric element heating methods have a superior ladle heating efficiency at point-of-use because there are no heat losses associated with the waste gas products of combustion. Ladle heating efficiencies in the melting shop of up to 90% have been claimed. Despite this, there are few, if any, examples of electric element ladle heaters in the UK, particularly for large ladle systems. In the United States electric ladle heaters have been tried for a range of ladle capacities. For 15 t ladles, units up to 150 kVA have been used with metallic elements with a maximum element temperature of 1,090°C, and units up to 250 kVA have been used with graphite elements with a maximum element temperature of 1,600°C. The maximum element temperature can limit ladle heating rates compared with combustion systems.

Larger installations include a 1,000 kW unit at Republic Steel's Canton Works for a 250 t degassing ladle. No major cost savings were reported for this system, and the electric elements were regarded as "high-maintenance" items.

Generally, the benefits of increased efficiency are outweighed by the higher unit cost of electrical energy. Also, the equipment can be relatively expensive to install and, due to its size and arrangement, can be vulnerable to damage within the melting shop environment. The main benefits are that the temperature can be controlled easily and the heaters are quiet, clean and non-polluting within the melting shop. The cost of pollution control is included in the electrical costs.

Unless electrical costs compare favourably, and remain stable relative to other fuels, it is unlikely that electric element heating equipment will reduce the overall ladle heating costs. However, new developments could change this situation, especially with the current trend towards combined heat and power (CHP) schemes. It may be possible to apply microwave technology to ladle heating/drying, although safety problems would need to be overcome to make this technology viable.

4. ACTION PLAN

The following list highlights actions that can be taken to improve ladle heating efficiency. Many are concerned with good housekeeping or simple monitoring but some may require specialist equipment and/or technical expertise. Where appropriate, advice should be sought from technical departments or external consultants.

4.1 Existing Installations

4.1.1 *Fuel Measurements and Metering*

Fuel metering should be installed and records of fuel usage should be kept on a regular basis. This allows the costs associated with fuel usage to be evaluated and highlights the need for maintenance when necessary. Data can also be used in statistical process control techniques to highlight changes in performance.

Energy records also assist with capital projects, allowing the return of investment to be evaluated and payback periods to be predicted.

4.1.2 *Hoods*

Refractory or ceramic fibre lined hoods should be used for all ladle heaters and these should be inspected regularly and kept in good condition.

The gap between the ladle rim and the hood should be set to the minimum level which does not cause burner back pressure problems.

For systems using heat recovery, where gases are ducted from the ladles, it is likely that efficiency will be optimised with a near perfect seal. It is therefore considered worthwhile to devise a suitable seal for the ladle geometry.

4.1.3. *Controls*

Temperature

Wherever possible, the ladle temperature should be controlled by adjusting the fuel input. Ladle temperature should be measured and the signals used to adjust the fuel supply rate automatically, preferably using a programmable logic controller. This will prevent unnecessary overheating, save fuel and reduce damage to refractories.

Chart records of ladle temperature variations can be used to check that the temperature control is working correctly and can also provide information on the quality of ladle heating related to other parameters, such as ladle life or yield losses.

Firing rate

The most suitable method of adjusting fuel rate at control temperature should be selected. High/low fire systems may produce wide variations in ladle pressure which, on horizontal stations, could lead to high air ingress. Full modulation control, where firing rates across the whole range from high to low fire are possible, can be more effective, but on low fire, penetration into the ladle base may be reduced. Impulse firing may overcome some of these problems, so long as the gap between the hood and rim is sufficiently small to minimise heat losses and avoid air ingress with the burner off. The most suitable system will depend upon the type of installation. Consultation with experts in this field may be useful, and equipment suppliers should explain the reasoning behind the selected method for any new installation.

4.1.4 *Good Housekeeping*

Adopt a good housekeeping policy by ensuring that ladles are returned to heating stations, or at least adequately covered, as soon as possible after use.

Encourage melting shop personnel to minimise the time for which ladles are allowed to cool prior to use. For example, it is wasteful to call for a ladle too early, since the heat supplied at the ladle station will dissipate into the atmosphere.

Avoid heating the ladles for longer than necessary - it is common to find ladles at heating stations for periods well in excess of the designated cycle. While in some cases a stand-by may be necessary to cater for emergencies, this is often used as an excuse. Better planning of ladle heating into the melting shop schedule is essential to avoid unnecessary fuel consumption.

Keep the ladle rims free from *skulling* since this will cause damage to the lid refractory and, in the case of horizontal stations, will prevent a good seal between the hood and rim. The build up of steel *skulling* may be reduced by the use of guards (or lip protectors) as described in Section 3.3.2.

4.1.5 *Heat Cycle Monitoring*

It is recommended that a monitoring exercise be carried out to establish the optimum ladle heating cycle for each melting shop. This can be done by simultaneously monitoring the internal and ladle shell temperature. The optimum heating cycle is the one which uses least fuel and yet allows safe and efficient practice.

To establish the point at which the ladle is dry, the emission of steam through *weep pores* can be monitored throughout the cycle. The time to reach the desired shell temperature will establish the required heating times.

Advice on acceptable heating rates on new ladles should be sought from refractory specialists.

An equilibrium point will be reached when shell temperatures no longer increase - heating beyond this period is wasteful and indicates that the ladle was placed on heat earlier than necessary. It should be noted that the equilibrium point may not necessarily be the optimum condition for ladle use. Whilst this will be the maximum quantity of heat that the bricks can store, it may be excessive for the particular requirements.

The optimum heating cycle will change whenever the refractory structure or composition is changed.

Ladle heating efficiency should be checked at regular intervals, especially with systems using heat recovery. An indication of efficiency can be obtained by measuring the oxygen content and temperature of the ladle exhaust gases and, where appropriate, by measuring the air pre-heat temperatures. This may require specialist monitoring equipment and the results should take into account the condition of the ladle at the time of the measurement.

For a detailed appraisal of efficiency, an energy balance should be carried out over a complete heating cycle with the ladle heating equipment in optimum condition to establish a reference for future measurements.

4.1.6 *Heat Recovery*

For existing cold air systems with available space it may be possible to add on a recuperator system to recover waste heat. This should be considered in conjunction with the comments in Section 4.2.

4.2 Selecting New Installations

4.2.1 *Horizontal versus Vertical Stations*

Factors such as space availability, plant layout and logistics may effect the reasoning behind selecting either vertical or horizontal orientation stations. In general terms, with adequately sized cold air burners, there are many operational advantages to using horizontal stations as described in Section 3.2.4. If horizontal stations are chosen, ladle rims must be kept clean and there must be a minimum gap between the burner hood and rim. Extra care should also be taken to ensure that the burner is not undersized.

For systems with heat recovery or oxy-fuel burners, pressurisation in the ladle will be more difficult to achieve. On horizontal stations it is critical to ensure a good seal between the hood and rim and use a high enough burner rating. It is also critical to minimise air ingress in order to achieve high efficiency.

On vertical stations, heat recovery methods are less likely to be impaired by air ingress and so higher efficiency may be possible.

4.2.2 *Hood Mechanisms*

The space available and the weight of the combustion equipment will dictate the hood lifting or swinging mechanisms that can be used.

Horizontal installations should be operated with the burner equipment on bogies and stationary ladles, because less damage results from hoods contacting ladles than vice versa.

4.2.3 *Burner Sizing*

Burner sizing, H_f (GJ/h), should be based on the maximum heating rate requirement of the ladle refractories, H_R (GJ/h), combined with the ladle heating efficiency μ (%) as described in Equation (1), Section 3.2.2.

H_R should be obtained from predictions using mathematical modelling, using designated heating cycles and ramp rates. An approximate check on the value of H_f can be obtained as described in Appendix 2, but this should not be used in isolation .

To ensure safety in operation, a factor of about 20% should be added to H_f for the actual burner size.

4.2.4 Waste Heat Recovery

Where appropriate, heat recovery systems should be given full consideration. In all cases, the comments made above with regard to sealing and optimum efficiency should be put into practice. The following notes may be helpful in the choice of system.

Recuperator System: Potential fuel saving compared with a cold air burner of up to 25%

The main advantage of this system is that the burner can operate independently of the recuperator. For example, a high velocity burner can be used in the normal way and, if temporary problems arise, say from air ingress, the extraction can be shut off. Also the location of the extraction ports is not restricted by the burner position, allowing some flexibility when initially setting up the system.

The main disadvantage of these systems is the relatively bulky equipment which may be difficult to accommodate on the ladle station, and the need for recuperator maintenance.

Self-Recuperative Burners: Potential fuel saving compared with a cold air burner of up to 25%

These are perhaps the lightest, most compact systems available for heat recovery, although one possible disadvantage is that the location of the extraction port is fixed in relation to the burner.

Vertical station systems are preferred, but these may require modified designs to avoid fall out of the burner refractory with the hood movement.

Regenerative Ceramic Burners: Potential fuel saving compared with a cold air burner of up to 40%

High efficiencies are possible with these systems, with opportunities for high fuel savings, and they have been used successfully on vertical stations. However, the relatively bulky equipment can be a disadvantage. The integral bed burner (IBB) is more compact, and could be suitable on some installations.

4.2.5 *Other Considerations*

Temperature and burner controls should be selected appropriately (as described for existing installations in Section 4.1). For systems where the gap between hood and rim is small, a thermocouple will normally suffice, but for more accurate measurement, especially with a large gap, infrared pyrometers aimed at the base can be used. When using pyrometers care should be taken to avoid aiming at the flame, or at *skulls* or slags left in the ladle.

Oxygen enriched burners should be considered where:

$$\frac{\text{Cost of supplying 100 m}^3\text{ (stp) of oxygen}}{\text{Cost of natural gas per GJ}} < 1.5$$

5. CASE STUDIES

The following case studies have been included to illustrate the benefits of using recuperation, self-recuperative burners, regenerative ceramic burners, oxygen enriched burners, hoods and programmable temperature control to improve ladle heating efficiencies.

Case Study 1: Ladle Heating with Horizontal High Velocity Burners and Exhaust Gas Heat Recovery.

EEDS Project Profile:	175
Host:	United Engineering Steels Limited, Brymbo, Clywd

Project Objectives

To compare pre-heating and drying using high velocity burners with and without waste heat recuperation.

Project Data

Ladle size:	90 tonnes
Brick type:	70% Alumina Graphite Magnesia on slag line.
Pre-heating practice:	Drying: 6-8 h, low fire. Sweating: 4-6 h, burner off. Fast heating to 900°C hold for 6 h.
Fuel:	Natural Gas

Equipment Details

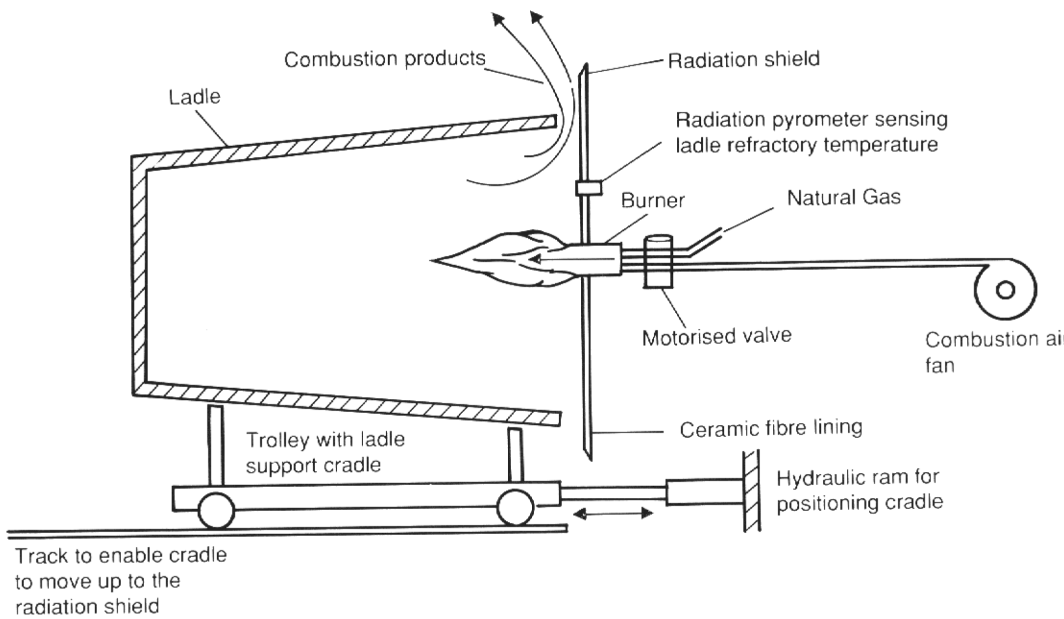
Ladles on bogies, stationary burner hoods (Fig 14).

(a) Horizontally fired HV burner.

Burner Rating:	5.3 GJ/h
Burner Control:	Radiation pyrometer refractory temperature measurement.

(b) Horizontally fired HV burner with waste heat recuperator

Burner Rating:	5.3 GJ/h
Burner Control:	Radiation pyrometer refractory temperature measurement. Direct control of combustion air valve. Electronic ratio control of gas and air flow.



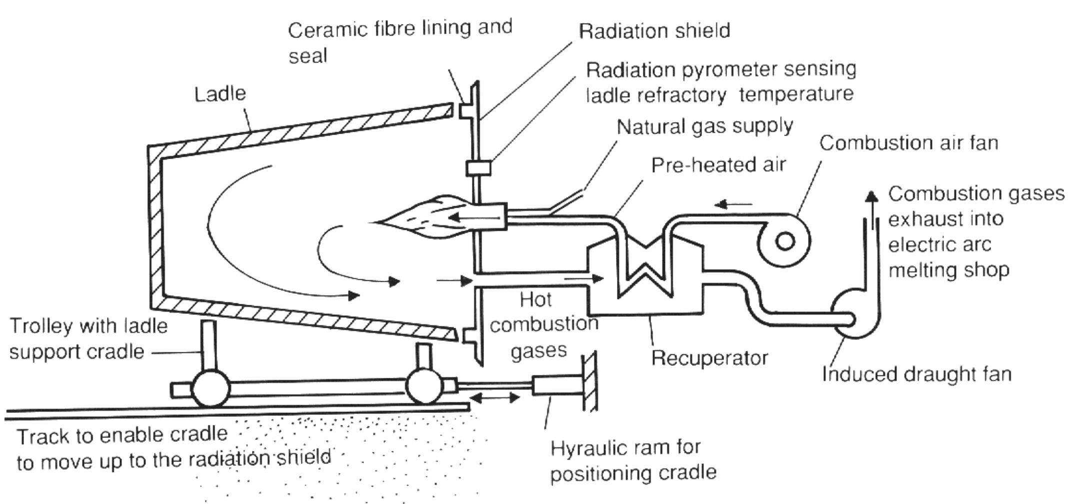


Fig 14 Horizontal ladle heaters with and without recuperation, UES Brymbo

Results

Table 2 Ladle heating results using recuperation

Measurements taken	HV burner	HV burner with recuperator	
		low air ingress	high air ingress
Average Fuel Usage: GJ/h	4.9	2.9	4.8
Ladle heating efficiency: %	Not measured	36.0	23.0
Air pre-heat: °C	–	250-300	
Energy saving claimed: %	–	25	

Comments

In general, each of the stations had problems of air ingress due to difficulties in minimising the gap between the ceramic fibre lined burner hood and the lower ladle rim. This was due to *skulls* on the ladle rim preventing a good seal and because the hoods were damaged as ladles approached the hood. The station with recuperation suffered the most because ladle gases were ducted through the hood making the ladle difficult to pressurise.

The two values of fuel usage and efficiency represent the best and worst values for the station with recuperation, dependent on the levels of air ingress. A ladle heating efficiency of 50% had been expected with the waste heat recuperation. Part of the cause of the poor performance was that the burner fired centrally with the exhaust port beneath; with a gap between hood and rim, cold air entered at the lower rim and short circuited directly into the exhaust port. This cooled the exhaust gases and so reduced air pre-heat temperatures.

An improved seal was devised (Fig 12(c)) and a significant improvement was reported. However, the seal was easily damaged and required regular maintenance. Eventually, even though the energy efficiency was improved with the seal, the exhaust port was blocked off and the recuperator removed.

It is considered that the project would have been more successful with the exhaust port placed in the upper section of the hood. In addition, ladle rims should have been kept clean to allow a better seal with the burner hood.

Future installations should have the combustion equipment on bogies and stationary ladles as this should result in less damage to the lid and any seal arrangement.

Case Study 2: Self-Recuperative Burner (SRB) on a Horizontal Station.

EEDS Project Profile: 145

Host: British Steel plc (now Avesta Sheffield Ltd), Stainless, Shepcote Lane, South Yorkshire.

Project Objective

To compare pre-heating and drying using high velocity burners and a self-recuperative burner (SRB).

Project Data

Ladle size: 130 tonnes

Brick type: 40-60% Alumina (Replaced by Dolomite at a later date)

Pre-heating practice:

Teeming Ladle — Drying: 8 h low fire
Heating: 1,100°C hot face, 150°C cold face.

Fuel: Coke Oven Gas
(Natural gas conversion, 1990 with a fuel oil back up).

Equipment Details

(a) Vertically fired HV burner, vertically pivoted hood mechanism.

Burner Rating: 7.9 GJ/h
Burner Control: Thermocouple temperature measurement.
Direct control of combustion air valve.
Backloaded zero gas governor.

(b) Horizontally fired HV burner, stationary ladle, combustion equipment on bogies.
Burner Rating: 7.9 GJ/h
Burner Control: Thermocouple refractory temperature measurement.
Control as for vertical station.

(c) Horizontally fired extended flue SRB arranged as (b) (Fig 15).
Burner Rating: 4.8 GJ/h
Burner Control: As for HV burners.

Results

Table 3 Ladle heating results using self-recuperative burners

Measurements taken	Vertical HVB	Horizontal HVB	Horizontal SRB
Average fuel input: GJ/h	3.0	5.8	4.8
Ladle heating efficiency: high fire %	35-37	17-27	29-31
low fire %	17-25	36	38
Air pre-heat: °C	N/A	N/A	215

Comments

As with Case Study 1, both horizontal stations suffered from air ingress at the lower rim of the ladle. This was exacerbated on the SRB due to the eduction of gases through the burner and because the burner was underrated for the duty. However, at the time of installation, the SRB was the largest of its type available and calculations indicated that, with the expected increase in efficiency, the burner rating would be adequate. This may have been possible with a near perfect seal between the rim and the burner hood.

In practice a gap existed and the pressure in the ladle was inadequate to overcome cold air ingress. The control temperature was rarely achieved and the burner remained on full fire throughout. Due to its inadequacy the SRB system has now been removed.

One of the difficulties in this case was that, initially, a ceramic fibre lining had been used to line the burner hoods which was easily damaged by *skulls* which commonly occurred on the ladle rims. As a result, the ceramic lining was replaced with a spray refractory which, because of its hard uneven surface, was unsuitable for a good seal with the ladle rim, even on unskulled ladles. The initial problem would have been reduced if the ladle rims had been kept clean.

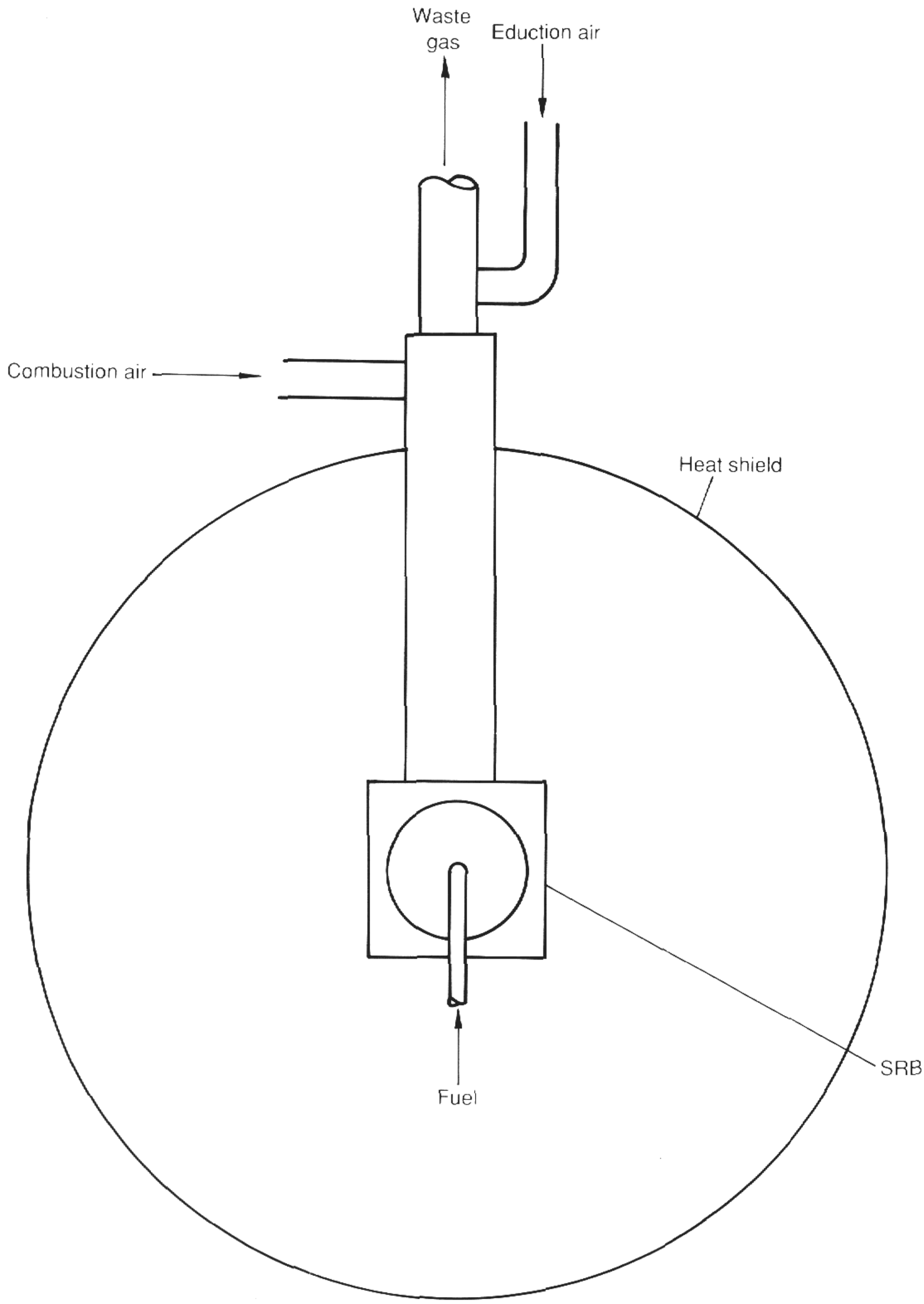


Fig 15 Schematic arrangement of self-recuperative burner

Notably, when the horizontal high velocity cold air burner was on high fire and a reasonably small gap was achieved between the hood and rim, the burner was sufficiently large to pressurise the ladle and prevent air ingress. In this condition the efficiency approximated to that of the vertical stations; however, it had all the advantages of a horizontal installation as described in Section 3.2. This installation is still used by the operators and was favoured over comparably-sized vertical stations.

A move to use basic linings (dolomite and graphite/magnesia) required faster heating rates and the vertical stations have now been replaced with vertical high velocity burners with a dual firing facility, rated at approximately 20.0 GJ/h. These burners produce very rapid heating rates and, whilst considered generally satisfactory, a failure of the temperature controllers on one station caused severe damage to the refractory hood. This demonstrates the extra vigilance necessary with overrated burners.

Case Study 3: Exhaust Gas Heat Recovery

EEDS Project Profile:	240
Host:	British Steel plc, Tubes, Clydesdale, Lanarkshire

Project Objective

To compare pre-heating drying using a horizontal regenerative ceramic burner (RCB) and horizontal cold air high velocity burners.

Project Data

Ladle size:	90 tonnes
Brick type:	60% Dolomite 40% Magnesite at strike plate and slag bubbler (Some 100% Magnesite).
Pre-heating practice:	Heating to 1,100°C in 6 h (high fire).
Fuel:	Natural Gas.

Equipment Details

Stationary ladles, burner equipment on bogies.

(a) Horizontally fired HV burner

Burner Rating:	10.6 GJ/h
Burner Control:	Manual high/low fire selection No temperature measurement. Differential gas governor.

(b) Horizontally fired RCB pair (Fig 16).

Burner Rating:	3.0 GJ/h (uprated from 1.6 GJ/h)
Supplementary horizontally fired HV burner	
Burner Rating:	2.4 GJ/h (downrated 4.2 GJ/h)
Burner Control:	Thermocouple refractory temperature measurement. Control of air valves on both RCB and HVB and tandem linked RCB exhaust valve. Multiplying regulator/gas governor control.

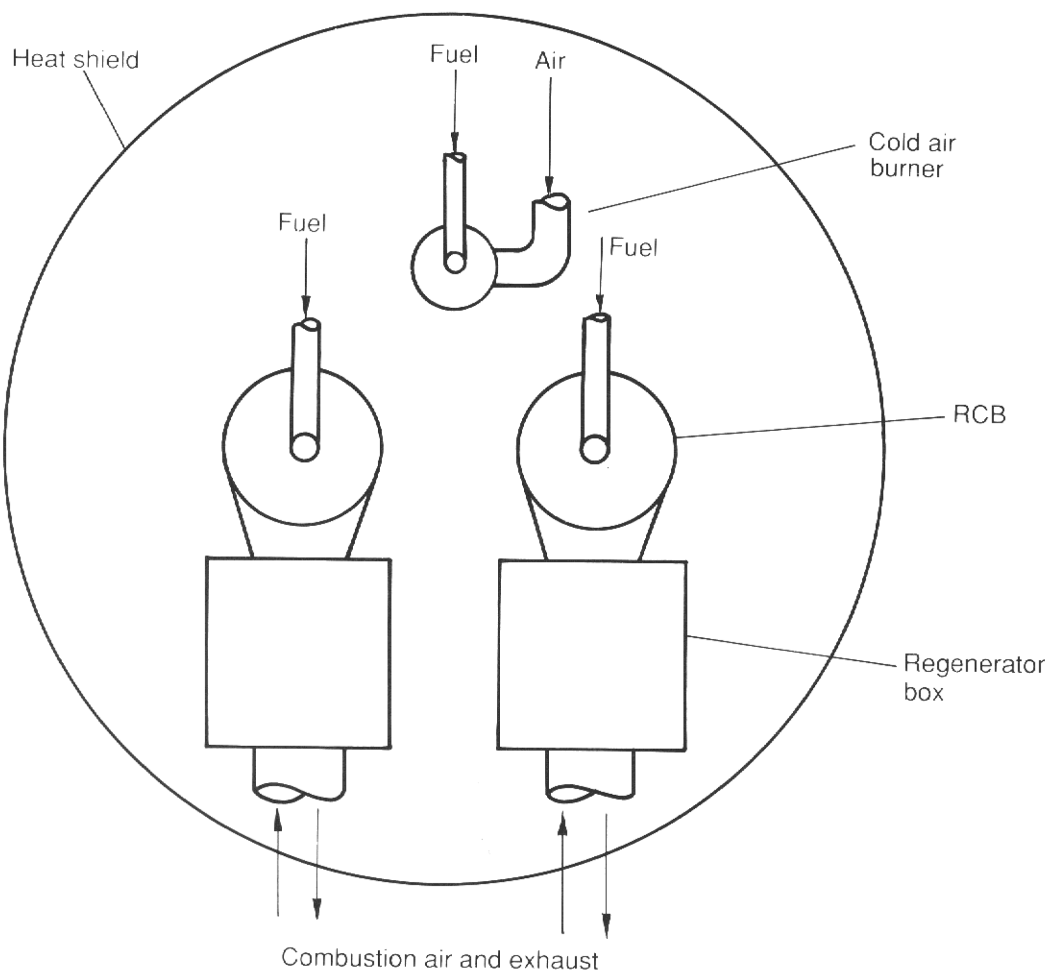


Fig 16 Schematic arrangement of regenerative and cold air burners, BS Clydesdale pre-heater

Results

Table 4 Ladle heating results using regenerative ceramic burners

Measurements taken	HV Burner	RCB/HV Burner
Average fuel usage: GJ/h	10.6	4.7
Ladle heating efficiency: %	20-22	33-48
Air pre-heat: °C	N/A	575
Energy saving claimed: %	–	46

Comments

The initial installation, which did not include the supplementary burner, was found to have similar problems to Case Studies 1 and 2; ie because of hot gas extraction, coupled with the relatively low burner rating, pressurisation was insufficient to prevent air ingress. An attempt was made to reduce air ingress using a curtain of compressed air on the lower rim. In good condition, this was only partially successful owing to the variable geometry of the gap. The equipment was, however, susceptible to damage and deteriorated in a short period until it could no longer be used.

The addition of the cold air supplementary burner improved the situation considerably and, with a sufficiently small gap, the improvements in efficiency and fuel usage, as described above, were achieved.

Several maintenance problems were encountered with damaged ceramic fibre on the burner hood and cracked burner *quarls* which on one occasion, due to the vibration from bogie-mounted fans, led to *quarl* collapse.

In general, the melting shop personnel consider that the station provided reasonable energy savings and adequate performance. A simple payback of three years was achieved.

Case Study 4: The application of hoods and programmable temperature controls to improve ladle heating efficiency.

EEDS Project Profile: 270

Host: North British Steel Group Ltd., Balbardie, West Lothian.

Project Objectives

Improvement of foundry ladle pre-heating by applying technology normally used on large steel works (refractory hoods and temperature control).

Project Data

Ladle size: 5 tonnes and 7 tonnes
Brick type: 63% Alumina, Firebrick, Rammed Duracrete base

Pre-heating practice: Heating to 1,000°C and holding.

Fuel: Natural Gas.

Equipment Details

(a) Vertically fired retention head burner open to atmosphere.

(b) Vertically fired retention head burner (Fig 17).

Burner Rating:	0.53 GJ/h
Burner Control:	Thermocouple refractory temperature measurement fed back to a programmable temperature controller. Direct control of combustion air valve. Air-impulsed back loaded gas governor.

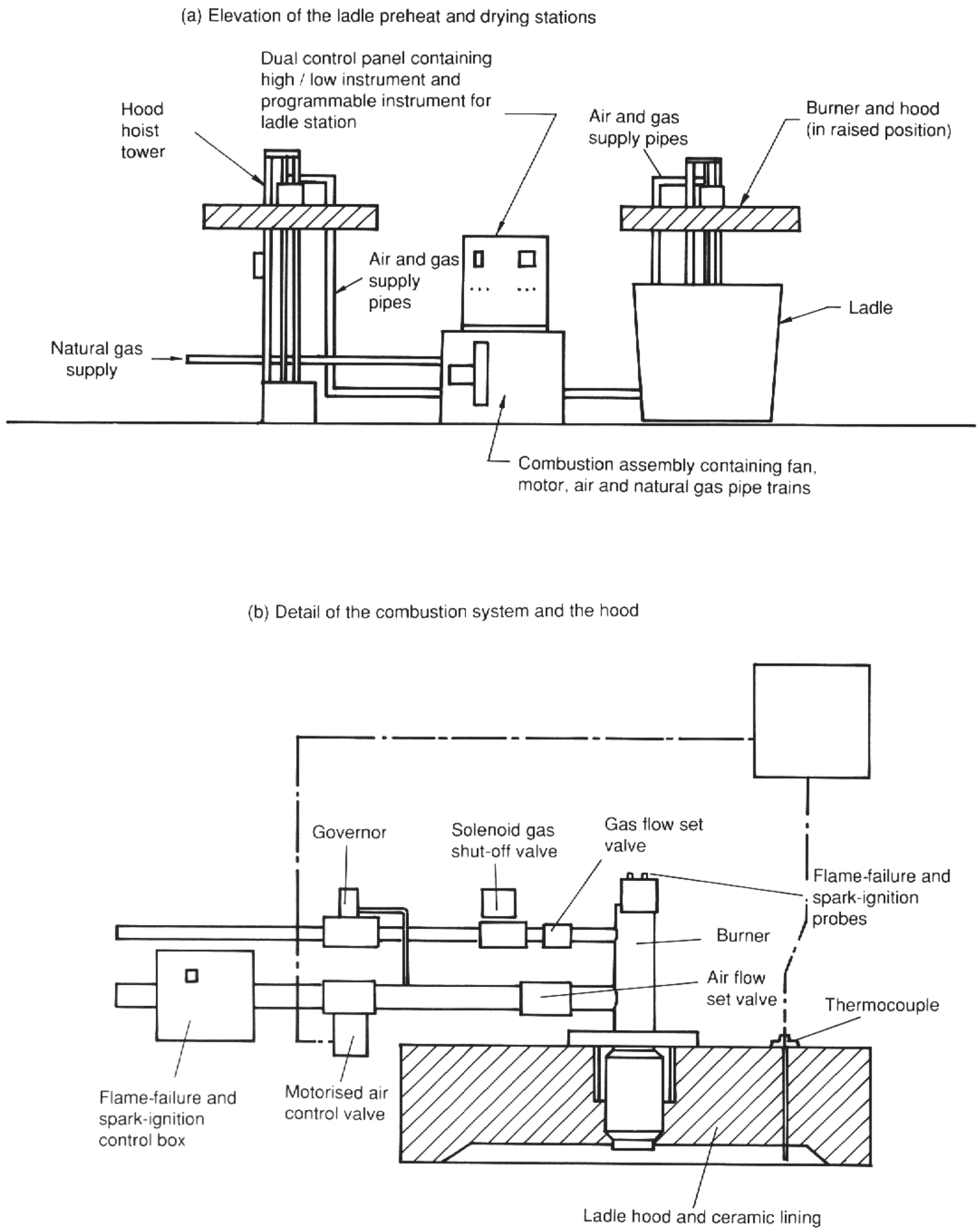


Fig 17 Ladle stations, North British Steel

Results

Table 5 Ladle heating results using hoods and programmable temperature controls

Measurements taken	Original Station	Modernised Station
Average fuel usage: GJ/h	1.22	0.63
Ladle heating efficiency: %	13.4-14.1	21
Energy saving claimed: %	–	59

Comments

This project demonstrates the importance of the use of hoods and temperature controls for efficient ladle heating, even with small ladle heaters.

Additional benefits, due to reduced yield losses, were reported. The project was an unqualified success with a 1.1 year payback.

Case Study 5: Oxygen Enriched Combustion

Host: Sheerness Steel, Sheerness, Kent

Project Objectives

Improvement of pre-heating efficiency by the application of oxy/fuel burners.

Project Data

Ladle size: 95 tonnes
Brick type: -

Pre-heating practice: Control temperatures set between 850°C and 1,100°C.

Fuel: Natural Gas

Equipment Details

Horizontally fired oxy/fuel burner

Burner Rating: 5.7 GJ/h
Burner Control: Optical Pyrometer and PLC selection of oxygen and fuel controls.

Comments

Four horizontal ladle pre-heaters have been fitted with oxy-fuel burners at Sheerness Steel and their performance assessed over one full year's operation. The results showed that although the expected cost savings were not achieved, the specific energy use of natural gas was reduced from 0.71 GJ/t to 0.36 GJ/t which, when weighted with the costs of oxygen, saved £0.18/tonne. However, this saving was achieved over a period when tonnage output increased by 22% and the effect of this on energy consumption relative to the effect of oxy-fuel burning is difficult to substantiate.

Availability has increased and maintenance costs, associated with burner *quarls*, front plates, fans and motors have been reduced. Further benefits have resulted from positioning the new ladle stations in an area where improved vision for crane drivers has reduced the damage to refractory burner hoods.

A payback period of 2-3 years was achieved.

APPENDIX 1

MEASUREMENT TECHNIQUES FOR ENERGY BALANCES ON LADLE PRE-HEATERS

Full Energy Balance

In performing a full energy balance, parameters must be measured over the whole heating cycle.

Parameter	Instrument	Comments
Fuel volume supplied	Positive displacement meters (Turbine) or differential pressure, dP, meters (Orifice Plate)	Installed in supply pipework
Fuel rate	Flow or signal transducer	Turbine meter signal amplifier
Combustion air flow	dP meter (Orifice Plate), or Pitot-static traverse in duct	
Oxygen concentration	Oxygen analyser	Sample probe and water vapour removal required
Ladle gas temperature	Suction pyrometer	To obtain exhaust gas temperatures place pyrometer near to gas exit
Refractory wall temperature	Infrared pyrometer or disappearing filament	
Ladle shell temperature	Infrared pyrometer or contact thermo-couple	Low temperature pyrometer
Air pre-heat temperature*	Suction pyrometer	
Waste gas temperature*	Suction pyrometer or thermocouple	

* where applicable (waste heat recovery systems)

Instantaneous Efficiency Values

A useful check on the instantaneous ladle heating efficiency can be made from measurements described below.

Parameter	Instrument	Comments
Oxygen concentration in combustion gases	Oxygen analyser	Sample probe and water vapour removal required
Ladle gas temperature	Suction pyrometer	To be measured at the gas exit points

APPENDIX 2

APPROXIMATION METHOD FOR BURNER SIZING

In order to approximate the heat requirement, H_R, the following assumptions have been made;

- The ladle is lined with a typical high density brick throughout (density = 2,850 kg/m^3).
- The ladle shell can be approximated by a cylinder with internal diameter D (m), height h (m). For tapered ladles this can be assumed to be the equivalent diameter at h/2 with a base diameter D_B. For elliptical shapes, D can be assumed to be the average of the major and minor internal diameters at h/2.
- The brick wall is of uniform thickness x (m), the base is of uniform thickness y (m).
- The average temperature of the brick is assumed to be the average of the hot face, THF (°C), and the ladle shell TCF (°C) .

  Both THF and TCF define the required ladle condition. To specify a heating rate it is assumed that this condition can be achieved in a time t(h), heated from cold (15°C).
- The specific heat C (J/kg°C) of the brickwork is defined at the average temperature as follows:

$$C = 930 + 0.2059 \left(\frac{THF + TCF}{2}\right)$$

- It is assumed that the ladle heating unit includes a hood, equivalent in diameter to the internal shell diameter at the top of the ladle D_T (m). The heat flux (W/m^2) to the hood is assumed to be equal to that at the sidewalls.
- In addition to the heat content of the ladle, a factor of about 10% should be added to allow for heat transmitted through the shell, ie a factor of 1.1 is included.

Then

$$H_R = \frac{1.1 \cdot 2{,}850}{t \cdot 10^9} .C. \left(\pi x\,(D - x)\,(h - y) + \frac{\pi D_B^2 y}{4}\right) \left(\frac{THF + TCF}{2} - 15\right) \left(1 + \frac{D_T^2}{4Dh}\right) \qquad \ldots (4)$$

The value of H_R (GJ/h) should be used in Equation (l) (Section 3.2.2) with the ladle heating efficiency, to approximate the burner size required. A worked example is shown below, in which a 20% safety factor has been added to ensure that the burner is not undersized. In practice an 'off-the-shelf' burner size may be suitable within this criterion.

Worked example of approximate burner requirements

D_T = 3.53 m
D_B = 2.94 m
x = 0.23 m
y = 0.31 m
h = 3.8 m
D = 3.24 m

Specification:
1,100°C hot face (THF)
200°C cold face (TCF), in 6h.

Therefore $\dfrac{\text{THF} + \text{TCF}}{2} = 650$

Using Equation (4):

$$C = 930 + (0.2059 \cdot 650) = 1{,}063$$

$$\left.\begin{array}{l}\left.\begin{array}{lcl} D\text{-}x &=& 3.01 \\ h\text{-}y &=& 3.49 \\ \pi x &=& 0.72 \end{array}\right\} \text{ Product} = 7.56 \\ \dfrac{\pi D_B^2 y}{4} = 2.1 \end{array}\right\} \text{ Sum } 9.66$$

$$1 + \frac{D_T^2}{4Dh} = 1.25$$

Therefore, burner requirement, H_R =

$$\frac{1.1 \cdot 2{,}850}{6 \, . \, 10^9} \cdot 1{,}063 \cdot 9.66 \cdot (650 - 15) \cdot 1.25 = 4.26 \text{ GJ/h}$$

To supply this rate of energy to the ladle (using equation (1) in Section 3.2.2):

- with a combustion efficiency of 50% (see Table 1, Section 3.2.2)

  Fuel requirement, $H_f = \dfrac{4.26}{0.5} = 8.5$ GJ/h

- with a combustion efficiency of 35%

  Fuel requirement, $H_f = \dfrac{4.26}{0.35} = 12.2$ GJ/h

With a cold air burner (depending upon the excess air level applied and, where applicable, whether air ingress occurs), the burner rating required would be between 8.5 and 12.2 GJ/h (81 therm/h to 116 therm/h). Providing that air/fuel ratio and air ingress could be adequately controlled, the lower burner rating would be adequate.

With a 20% safety factor 10.2 GJ/h would be a suitable burner size to install (98 therm/h).

APPENDIX 3

SUPPLIERS OF COMBUSTION LADLE HEATERS

The following list of suppliers has been included to assist potential users of ladle heating equipment. The list is not exhaustive and has been compiled from data currently available to ETSU. The listing of an organisation does not constitute an endorsement by the DoE of its competence. Further organisations may be found in commercially available trade directories. Non-listing of an organisation does not discriminate against its competence.

Regenerative

Hotwork International Ltd
Bretton Street
Savile Town
Dewsbury
West Yorkshire WF12 9DB
Tel. No. 01924 465272

Stirling Process Engineering Ltd
Brunel Road
Rabans Lane
Aylesbury
Bucks HP19 3SS
Tel. No. 01296 87171

Stordy Combustion Eng. Ltd
Heathmill Road
Wombourne
Wolverhampton
W Midlands
Tel. No. 01902 897654

Self-recuperative and other burner types

Actric Ltd
Brandon Way
West Bromwich
West Midlands B70 9PE
Tel. No. 0121 553 0728

Laidlaw Drew & Co. Ltd
1 Lister Road
Kirkton Campus
Livingstone EH54 7BL
Tel. No. 01506 416666

CGE Kilns and Dryers Ltd
Unit 6
Peel Road
West Pimbo, Skelmersdale
WN8 9PT
Tel. No. 01695 27441

Nu-Way Ltd
PO Box 1
Vines Lane
Droitwich
Worcs. WR9 8NA
Tel. No. 01905 794331

Eurograde Ltd
Unit 3
Viscount Industrial Estate
Horton Road
Poyle, Colnbrook
Berks SL3 0DS
Tel. No. 01753 681890

Stordy Combustion Eng. Ltd
Heathmill Road
Wombourne
Wolverhampton
W Midlands
Tel. No. 01902 897654

Hotwork International Ltd
Bretton Street
Savile Town
Dewsbury
West Yorkshire WF12 9DB
Tel. No. 01924 465272

Burns Engineering
Droicon Estate
Portway Road
Rowley Regis
Warley
West Midlands B65 9BZ
Tel. No. 0121 559 6601

Mont Selas Ltd
8-20 City Road East
Manchester M15 4PJ
Tel. No. 0161 228 0120

Recuperators – high temperature

Acoustics & Envirometrics (AEL) Ltd
Berkeley Court
Stuart Road
Manor Park
Runcorn
Cheshire WA7 1TQ
Tel. No. 01928 579068

Therm Tech Engineering Ltd
Unit One
North End Road Ind Est
Knowl Street
Stalybridge SK15 3AZ
Tel. No. 0161 303 8383

Stirling Process Engineering Ltd
Brunel Road
Rabans Lane
Aylesbury
Bucks HP19 3SS
Tel. No. 01296 87171

Mont Selas Ltd
8-20 City Road East
Manchester M15 4PJ
Tel. No. 0161 228 0120

Stirling Process Engineering Ltd
Brunel Road
Rabans Lane
Aylesbury
Bucks HP19 3SS
Tel. No. 01296 87171

Wellman Furnaces Ltd
Cornwall Road
Smethwick
Warley
West Midlands B66 2LB
Tel. No. 0121 558 3151

Monometer Holdings Ltd
Monometer House
Rectory Grove
Leigh-on-Sea
Essex SS9 2HN
Tel. No. 01702 72201

Hotwork International Ltd
Bretton Street
Savile Town
Dewsbury
West Yorkshire WF12 9DB
Tel. No. 01924 465272

Metallurgical Engineers
Boundary House Ltd
Boston Road
London W7 2QQ
Tel. No. 0181 567 9612

Wilkins & Wilkins Ltd
Sterte Avenue West
Poole
Dorset BH15 2BD
Tel. No. 01202 673174

APPENDIX 4

BURNER FIRE RATE TO OVERCOME BUOYANCY ON HORIZONTAL STATIONS

Equation 5 (below) can be used to determine the burner firing rate to overcome buoyancy as described in the worked example below.

Worked Example: Cold Air Burner

Ladle gas temperature	= 1,100°C = 1,373 K
Ladle diameter, D	= 3.0 m
Excess air level	= 10%
Fuel	= Natural gas
Ambient temperature	= 15°C = 288 K
Gap between lid and ladle rim, X	= 0.05 m
Ladle gas density	= P_g
Air density	= P_a

Using the following equation:

$$\boxed{Q = Dx\sqrt{\frac{\pi}{2}\ Dg\left(\frac{P_a}{P_g} - 1\right)}} \qquad \ldots (5)$$

Assume that the ladle gas density approximates to that of air at the same temperature then

$$\frac{P_a}{P_g} = \frac{T_g}{T_a} = \frac{1{,}373}{288}$$

$$Q = 3.0 \cdot 0.05\sqrt{\frac{\pi}{2}\ 3.0 \cdot 9.8\left(\frac{1{,}373}{288} - 1\right)}$$

$$= 1.98\ m^3/s$$

The equivalent flow at stp (0°C, 1 Atm) is Q_{stp} where

$$Q_{stp} = \frac{273}{1{,}373} \times 1.98 = \mathbf{0.39\ m^3/s}$$

This is the volume flow of combustion products (at stp) required to maintain the required ladle pressure to avoid air ingress.

To relate this to the fuel requirement, V_f, the stoichiometry of natural gas combustion must be considered.

Volumes required	$\frac{CH_4}{V_f}$	$\frac{O_2 + N_2}{(9.75 + 0.975)V_f}$	—>	$\frac{CO_2 + H_2O}{10.78\ V_f}$	$\frac{O_2 + N_2}{0.975\ V_f}$

Note 0.975 = 10% excess air

Total volume of combustion product = 11.76 x fuel volume
= 11.76 x V_f

Thus to produce 0.39 m^3/s of combustion products, the fuel required $= \frac{0.39}{11.76}$

$= 0.033\ m^3/s$

Thus the fuel requirement (stp) = 0.033 m^3/s
= 119.4 m^3/h

Based on a gross energy content of 40.74 MJ/m^3, this equates to an energy output of 4.86 GJ/h (equivalent to a burner rating of 46 therm/h).

APPENDIX 5

CALCULATION OF PRESSURE IN A LADLE BASED ON A COLD AIR BURNER

$$\boxed{P = 5.854 \cdot 10^{-8}\, T \left(\frac{F}{Dx} \right)^{2}} \qquad \ldots (6)$$

where P = Pressure within ladle assuming no ingress due to buoyancy effects (mbar)
T = Temperature in ladle (K)
F = Burner firing rate (GJ/h)
D = Ladle diameter (m)
x = Gap between hood and ladle rim (m)

Examples

1. Pressure for a given gap size

Let,
T = 1,373K
x = 0.15 m
D = 3.2 m
F = 8.44 GJ/h

$$P = 5.854 \cdot 10^{-8} \cdot 1{,}373 \left(\frac{8.44}{3.2 \cdot 0.15} \right)^{2}$$

P = 0.0249 mbar

2. Gap size for a given pressure of 0.05 mbar

$$x = 2.42 \cdot 10^{-4} \cdot \frac{F}{D} \sqrt{\frac{T}{P}}$$

Let,
F = 10.55 GJ/h
D = 3.5 m
T = 1,100°C = 1,373K
P = 0.05 mbar

$$x = 2.42 \cdot 10\text{-}4 \cdot \frac{10.55}{3.5} \sqrt{\frac{1{,}373}{0.05}}$$

x = 0.121 m

APPENDIX 6

GLOSSARY OF TERMS

Buoyancy	the difference in densities between hot combustion gases inside the ladle and ambient temperature air outside the ladle.
Ganged Valve Assemblies	both the air and fuel are controlled by a single motorised valve controller.
Hot Face	the higher temperature refractory surface exposed to process heat.
Impulse Control	the rate of thermal input is controlled by switching burners on and off, with the burners operating on only one single firing rate.
Ladle Shell	the outer metal casing of the ladle, enclosing the refractory materials.
Modulation Control	the rate of the thermal input is controlled by burners able to operate through a continuous range of low fire rate to high fire rate.
Premix Burners	burners which require air and fuel to be mixed before reaching the burner.
Quarl	the refractory components surrounding the burner nozzle.
Skull	a build up of steel on the ladle rim.
Slagline	the region of a ladle internal wall which is exposed to slag floating on the molten steel surface.
Striker Pads	the area of refractory at the base of the ladle which takes the impact of molten steel when poured into the ladle.
Teeming	pouring molten steel into ingot moulds or a continuous canter.
Weep pores	pores in the ladle structure which allow "wet" products to escape from the ladle when drying.

For further information on this or other buildings-related projects, please contact: Enquiries Bureau, Building Research Energy Conservation Support Unit (BRECSU), Building Research Establishment, Garston, Watford WD2 7JR. Tel No 0923 664258. Fax No 0923 664097.

For further information on industrial projects, please contact the Energy Efficiency Enquiries Bureau, Energy Technology Support Unit (ETSU), Building 156, Harwell Laboratory, Oxon OX11 0RA. Tel No. 0235 436747. Telex No. 83135. Fax No. 0235 432923.